Institutionen för datavetenskap
Department of Computer and Information Science

Final thesis

Evaluation of Model-Based Testing on a Base Station Controller

by

Stefan Trimmel

LIU-IDA/LITH-EX-A--08/023--SE

2008-06-10

Linköpings universitet

Linköpings universitet
SE-581 83 Linköping, Sweden

Linköpings universitet
581 83 Linköping

Linköping University
Department of Computer and Information Science

Final Thesis

Evaluation of Model-Based Testing on a Base Station Controller

by

Stefan Trimmel

LIU-IDA/LITH-EX-A--08/023--SE

2008-06-10

Supervisor: Henrik Green, Ericsson BSC Design, FT & Test Enviroment

Examiner: Erik Larsson, LiTH-IDA, Embedded Systems (ESLAB)

Abstract

This master thesis investigates how well suited the model-based testing process is for testing a new feature of a Base Station Controller. In model-based testing the tester designs a behavioral model of the system under test, or some part of the system. This model is then given to a test generation tool that will analyze the model and produce interesting test cases. These test cases can either be run on the system in an automatic or manual way depending on what type of setup there is.

In this report it is suggested that the behavioral model should be produced in as early a stage as possible and that it should be a collaboration between the test team and the design team.

The advantages with the model-based testing process are a better overview of the test cases, the test cases are always up to date, it helps in finding errors or contradictions in requirements and it performs closer collaboration between the test team and the design team. The disadvantages with model-based testing process are that it introduces more sources where an error can occur. The behavioral model can have errors, the layer between the model and the generated test cases can have errors and the layer between the test cases and the system under test can have errors. This report also indicates that the time needed for testing will be longer compared with manual testing.

During the pilot, when a part of a new feature was tested, of this master thesis a test generation tool called Qtronic was used. This tool solves a very challenging task which is generating test cases from a general behavioral model and with a good result. This tool provides many good things but it also has its shortages. One of the biggest shortages is the debugging of the model for finding errors. This step is very time consuming because it requires that a test case generation is performed on the whole model. When there is a fault in the model then this test generation can take very long time, before the tool decides that it is impossible to cover the model.

Under the circumstances that the Qtronic tool is improved on varies issues suggested in the thesis, one of the most important issues is to do something about the long debugging time needed, then the next step can be to use model-based testing in a larger evaluation project at BSC Design, Ericsson.

Preface

This report is my final thesis on my Master Degree in Computer Science at Linköping University. I started to work with this master thesis at Ericsson in Linköping the 2008-01-21 and presented the result the 2008-06-02.

People that have contributed to this report in some way are without any order are my examinator Erik Larsson, my supervisor at Ericsson Henrik Green, Mariam Kamkar, Ludmila Ohlsson, Patrik Nandorf, Pär Emanuelsson, Jan Svensson, Håkan Peterson, Andreas Almén, Mats Karlsson, Patrik Ekberg, Lars Erik Rosengren and my room-mates Johan Malmborg, Niklas Eriksson and Stina Måhl

I have also received some help from people from Conformiq. I would like to thank Jani Koivulainen, Michael Mandahl, Kimmo Nupponen and Nikolaj Cankar.

Thank you!

Stefan Trimmel

Contents

ABSTRACT V

PREFACE VII

CONTENTS IX

LIST OF FIGURES XIII

LIST OF TABLES XIV

1 ACRONYMS DICTIONARY 1

2 INTRODUCTION 3

2.1 PURPOSE 3
2.2 READING INSTRUCTIONS 3

3 SOFTWARE TESTING 5

3.1 OBJECTIVE OF SOFTWARE TESTING 6
3.2 DIFFERENT KIND OF TESTING 6
3.2.1 UNIT TEST 7
3.2.2 COMPONENT TESTING 7
3.2.3 INTEGRATION TESTING 7
3.2.4 SYSTEM TESTING 7
3.2.5 WHITE BOX TESTING 7
3.2.6 BLACK BOX TESTING 7
3.2.7 FUNCTIONAL TESTING 8
3.2.8 ROBUSTNESS TESTING 8
3.2.9 PERFORMANCE TESTING 8
3.2.10 USABILITY TESTING 8

4 MODEL-BASED TESTING 9

4.1 INTRODUCTION STORY 9
4.2 WHAT IS MODEL-BASED TESTING? 10
4.3 THE MODEL-BASED TESTING PROCESS 11
4.4 BENEFITS WITH MODEL-BASED TESTING 13
4.4.1 COMPREHENSIVE TESTS 13
4.4.2 TIME REDUCTION 14

4.4.3 FINDING REQUIREMENT DEFECTS 14
4.4.4 REQUIREMENTS EVOLUTION 14
4.4.5 REQUIREMENT VALIDATION 14
4.4.6 TRACEABILITY 14
4.5 DRAWBACKS WITH MODEL-BASED TESTING 15
4.5.1 TESTING SKILLS 15
4.5.2 SPLITTING AND MERGING MODELS 15
4.5.3 STATE SPACE EXPLOSION 16
4.5.4 TIME TO ANALYZE FAILED TESTS 16
4.5.5 OTHERS 16

5 CONSTRUCTING A MODEL 17

5.1 MODEL GUIDELINES 17
5.2 DIFFERENT MODEL NOTATIONS 18
5.2.1 DATA-FLOW NOTATIONS 18
5.2.2 FUNCTIONAL NOTATIONS 18
5.2.3 HISTORY-BASED NOTATIONS 18
5.2.4 OPERATIONAL NOTATIONS 19
5.2.5 STATE-BASED (PRE/POST) NOTATIONS 19
5.2.6 STATISTICAL NOTATIONS 20
5.2.7 TRANSITION-BASED NOTATIONS 21

6 TEST CASE GENERATION 23

6.1 STRUCTURAL MODEL COVERAGE CRITERIA 23
6.1.1 CONTROL-FLOW 23
6.1.2 DATA-FLOW 26
6.1.3 TRANSITION-BASED 28
6.1.4 UML-BASED 31
6.2 DATA COVERAGE CRITERIA 32
6.2.1 BOUNDARY VALUE TESTING 32
6.2.2 STATISTICAL DATA COVERAGE 34
6.3 REQUIREMENTS-BASED CRITERIA 34
6.4 EXPLICIT TEST CASE SPECIFICATIONS 35

7 CONFORMIQ QTRONIC – PILOT MODELING TOOL 37

7.1 CONFORMIQ 37
7.2 QTRONIC MODELER 37
7.2.1 QML – QTRONIC MODELING LANGUAGE 37
7.2.2 EXAMPLE 39
7.3 QTRONIC 42
7.4 ONLINE TESTING 42
7.5 OFFLINE TEST GENERATION 43
7.5.1 SCRIPT GENERATION 43

7.6 MODEL COVERAGE METHODS 44
7.6.1 STATE CHARTS (STATE MACHINE) 44
7.6.2 CONDITIONAL BRANCHING 44
7.6.3 CONTROL FLOW 45
7.6.4 ALL PATHS COVERAGE 45
7.7 MODEL CHECKING 45

8 PILOT 47

8.1 GSM/GPRS NETWORK 47
8.2 MANUAL TESTING PROCEDURE 48
8.3 THE MODELED FEATURE - RTTI 49
8.3.1 BASIC TRANSMISSION TIME INTERVAL (BTTI) 49
8.3.2 REDUCED TRANSMISSION TIME INTERVAL (RTTI) 49
8.4 MODEL DELIMITATIONS 50
8.5 MODEL-BASED TESTING PROCESS DELIMITATIONS 50
8.6 INPUT DOCUMENTS 51
8.7 MODELING TOOL 52
8.8 TEST CASE GENERATOR 52
8.9 ANALYZE GENERATED TEST CASES 52
8.10 MEASUREMENTS 53
8.11 MODEL COVERAGE SETUP 54
8.11.1 SETUP 1 54
8.11.2 SETUP 2 54

9 PILOT MODEL 55

9.1 MOBILE STATIONS (MS) STATE MACHINE 55
9.1.1 SIGNALS 56
9.2 CONNECTION CONTROL (CC) STATE MACHINE 56
9.2.1 SIGNALS 57
9.3 CHANNEL UTILIZATION (CU) STATE MACHINE 57
9.3.1 DYNAMIC TTI MODE 58
9.3.2 TBF RESERVATION 58
9.3.3 FAULTY CHANNEL 60
9.3.4 SIGNALS 61
9.4 TBF RESERVATION SIGNALING 61
9.5 FAULTY CHANNEL SIGNALING 62

10 PILOT RESULTS 63

10.1 THE EXPERTS' POINTS 63
10.1.1 MODEL-BASED TESTING 63
10.1.2 MANUAL TESTING 63
10.2 TEST COVERAGE OF TBF RESERVATION PART 64
10.3 TEST COVERAGE OF FAULTY CHANNEL PART 64

10.4 CONSUMED TIME **65**
10.4.1 MANUAL TESTING 65
10.4.2 MODEL-BASED TESTING 65
10.5 OVERVIEW OF THE TEST SCOPE **67**
10.6 FLEXIBILITY TO ADJUST THE TEST SCOPE/COVERAGE **68**

11 LESSONS LEARNED WHEN MODELING **69**

11.1 GUIDELINES **69**
11.1.1 QTRONIC RANDOM FUNCTION 69
11.1.2 USE REQUIRE ON SIGNALS 70
11.1.3 USE ONLY FINALIZED RUNS WHEN POSSIBLE 70
11.1.4 RECORD AND CLASS NAMING 72
11.1.5 ONLY BASIC TYPES IN RECORDS 72
11.1.6 PREVENT DEADLOCKS 72
11.1.7 DON'T USE THE TRACE FUNCTION 73
11.1.8 USE ASSERTIONS FOR FINDING BUGS 73
11.1.9 SELF-LOOPS WITH NO SIGNAL ON THE TRANSITION 74
11.2 FOUND BUGS IN QTRONIC **74**
11.2.1 SELF-LOOPS 74
11.2.2 QTRONIC SIGNAL VALUE AS ARGUMENT TO A METHOD 76
11.2.3 VECTOR POSITION 13 77
11.2.4 LONG TEXT STRING IN SIGNAL VALUE 78
11.2.5 QTRONIC TRACE() FUNCTION 79
11.3 SUGGESTIONS OF IMPROVEMENTS OF THE QTRONIC TOOL **79**
11.3.1 ECLIPSE INTEGRATION 79
11.3.2 VIEWING A TEST CASE TRACE IN THE MODEL 80
11.3.3 DEBUGGING 80
11.3.4 RANDOMIZE THE NONE IMPORTANT INPUT VALUES SELECTION 82
11.3.5 USING IDLE COMPUTERS FOR TEST GENERATION 83

12 CONCLUSION AND FUTURE WORK **85**

12.1 CONCLUSION **85**
12.2 FUTURE WORK, NEXT STEP **87**

REFERENCES **89**

APPENDIX A: MULTI SLOT CLASS TABLE **91**

List of figures

Figure 3.2.1 Different kind of testing ___ *6*
Figure 4.2.1 Model-Based Testing in the testing process ___ *10*
Figure 4.3.1 Model-Based Testing process ___ *12*
Figure 4.4.1 Traceability ___ *15*
Figure 5.2.1 Message sequence chart (MSC) ___ *19*
Figure 5.2.2 Petri net ___ *19*
Figure 5.2.3 Simple finite state machine ___ *21*
Figure 6.1.1 Control-flow hierarchy ___ *24*
Figure 6.1.2 Data-flow hierarchy ___ *27*
Figure 6.1.3 All-definitions example ___ *27*
Figure 6.1.4 All-uses example ___ *27*
Figure 6.1.5 All-definition-use-paths example ___ *27*
Figure 6.1.6 State chart ___ *28*
Figure 6.1.7 Finite state machine ___ *28*
Figure 6.1.8 Transition hierarchy ___ *29*
Figure 6.1.9 All-loop-free-paths example ___ *30*
Figure 6.2.1 Easy data coverage example ___ *32*
Figure 6.2.2 Integer example of boundary points of a shape ___ *33*
Figure 6.2.3 Boundary value testing hierarchy ___ *33*
Figure 7.2.1 QML, Java and UML ___ *37*
Figure 7.2.2 Free individuals example ___ *39*
Figure 7.2.3 Free individuals state machine ___ *40*
Figure 7.2.4 Test case using general model ___ *41*
Figure 7.2.5 Test case generated using guide model ___ *41*
Figure 7.3.1 Qtronic overview ___ *42*
Figure 8.1.1 GSM/GPRS Network ___ *47*
Figure 8.2.1 Manual testing process ___ *48*
Figure 8.3.1 BTTI timeslot example ___ *49*
Figure 8.3.2 RTTI timeslot example ___ *50*
Figure 8.5.1 General MBT compared with the process used in the pilot ___ *51*
Figure 9.1 Overview of the pilot model ___ *55*
Figure 9.3.1 Timeslot frame in CU ___ *57*
Figure 9.3.2 TBF reservation algorithm in CU ___ *59*
Figure 9.3.3 RTTI allocation examples ___ *59*
Figure 9.3.4 BTTI allocation examples ___ *60*
Figure 9.3.5 Faulty Channel algorithm in CU ___ *61*
Figure 9.4.1 Signaling when a TBF is reserved ___ *62*
Figure 9.5.1 Signaling when a channel becomes faulty ___ *62*
Figure 10.3.1 Example of a test case that ended too quickly ___ *64*
Figure 10.4.1 Consumed time in the pilot ___ *66*
Figure 11.1.1 Only Finalized Runs example ___ *71*
Figure 11.1.2 System deadlock ___ *73*
Figure 11.1.3 State machine with self-loop without a signal ___ *74*
Figure 11.2.1 Self-loop making Qtronic unable to generate test cases ___ *75*
Figure 11.3.1 Traceable test cases in the model ___ *80*
Figure 11.3.2 Sketch of new debugging feature ___ *81*
Figure 11.3.3 Use cage of multi slot classes in different test cases ___ *82*
Figure 11.3.4 Use idle computer for test generation ___ *83*

List of tables

Table 6.1.1 Test pattern for fulfilling MC/DC ____ *25*
Table 6.1.2 Test pattern for MCC ____ *26*
Table 7.2.1 Difference between Java and QML ____ *38*
Table 8.9.1 Names on the persons in the expert group ____ *52*
Table 8.11.1 Pilot coverage setup 1 ____ *54*
Table 8.11.2 Pilot coverage setup 2 ____ *54*
Table 9.1.1 Input and output signals in MS ____ *56*
Table 9.2.1 Input and output signals in CC ____ *57*
Table 9.3.1 Input and output signals in CU ____ *61*
Table 10.1.1 Points given by the experts on the Model-Based Testing ____ *63*
Table 10.1.2 Points given by the experts on the Manual Testing ____ *63*
Table A.1 Multi slot classes ____ *91*

1 Acronyms dictionary

API – Application Programming Interface

BSC – Base Station Controller

BSS – Base Station System

BTS – Base Transceiver Station

BTTI – Basic Transmission Time Interval

CC – Connection Control

CCCH – Common Control CHannel

CU – Channel Utilization

FANR – Fast Ack/Nack Reporting

FD – Function Description

FS – Function Specification

FSM – Finite State Machine

GSM – Global System for Mobile Communications

HTML – Hyper Text Markup Language

IP – Implement Proposal

MBT – Model-Based Testing

MS – Mobile Station(s)

MSC – Message Sequence Charts

OCL – Object Constraint Language

OO – Object Oriented

OS – Operating System

PACCH – Packet Associated Control CHannel

PDCH – Packet Data Channel

QML – Qtronic Modeling Language	
RBS – Radio Base Station	
RS – Requirement Specification	
RTT – Round Trip Time	
RTTI – Reduced Transmission Time Interval	
SDL – Specification and Description Language	
SUT – System Under Test	
TBF – Temporary Block Flow	
TCL – Tool Command Language	
TTI – Transmission Time Interval	
TTNC-3 – Testing and Test Control Notation version 3	
UML – Unified Markup Language	

2 Introduction

The Ericsson department BSC Design (Base Station Controller), designs and tests the BSC node in the GSM network. The BSC organization delivers BSCs to customers around the world. With more than 200 customers using Ericsson's BSC, the product line is very profitable. The Ericsson BSC product includes functionality for GPRS and EDGE as well as standard traffic handling and configuration of the radio network.

The Linköping based GSM/EDGE Development Centre is responsible for SW development of the BSC node in the GSM system. Their responsibilities are product development and maintenance of radio network products.

The process used by the BSC Function Test when testing is at the moment manual testing. One drawback with manual testing is that it is easy to miss some interesting test case that should have been tested. It is also hard to get a clear overview of that is tested and what is not tested.

The BSC Design has lately got many new employees and therefore it is a good time to test a new testing methodic.

2.1 Purpose

This master thesis will investigate how Model-Based Testing (MBT) can be used in Function Test of the BSC and propose how to work with MBT.

During the master thesis a pilot will be built, showing that it is possible to use the model-based testing approach at the BSC department. The pilot will also give concrete suggestions on what to think about when producing a model for model-based testing.

The result from the pilot will be examined by a group of experts from Ericsson BSC department, and they will compare the pilot with the normal manual testing that is performed at BSC Design.

2.2 Reading instructions

This report tries to introduce model-based testing in a way so that no or little pre knowledge of model-based testing is needed.

Chapter 3 introduces what software testing is.

Chapters 4-6 describe what model-based testing is, how to build models and how test cases can be extracted from the model. These chapters try to have a wide view on model-based testing.

The remaining chapters are focused on the pilot and the generation tool that was used during the pilot. Chapter 7 is the starting point of the pilot which was performed in the master thesis, here the test generation tool that was used is described.

In chapters 8-9 the feature that the pilot will model is described and also what the created model looked like.

The outcome of the model can be read in chapters 10-11. Chapter 10 is a summary of what the expert group thought about the result of the pilot and chapter 11 clarifies what about things to think about when modeling with the Qtronic tool.

The conclusions are presented in chapter 12.

3 Software testing

Software testing is the main key tool for software quality assurance. Often very large amount of time is spent on software testing during the process of software development. Therefore it is in interest of all companies that produce software to do the testing in a smart and efficient way so that the margin of the product will be maximized.

One definition of software testing can be found in IEEE *Software Engineering Body of Knowledge* (2004).

> Software testing consists of the *dynamic* verification of the behavior of a program on a *finite* set of test cases, suitably *selected* from the usually infinite executions domain, against the *expected* behavior.

The words in italic are important and needs some more explanations.

Dynamic: This term means that the program or system under test is executed with specific input values to find failures in its behavior. The opposite of dynamic is static and in this type of analysis, execution of the system is not required. Static analysis can be inspections or walkthroughs. One of the good features with dynamic techniques is that we execute the actual program in its real environment of a simulated environment as close as possible to the real environment. So you are not only testing the program or system but also everything around it, compiler, libraries, and operating system and so on. This is not done in the static techniques.

Finite: It is often impossible to test every test pattern, even for small programs. The number of test patterns grows very fast with more input parameters and valid data and invalid or unexpected input data. If you consider different test sequences with the same input data but in a different order to be unequal then the number of test cases needed almost grows to infinity. Time is always against you therefore it is necessary to select a good set of finite test cases to execute.

Selected: Since there are almost infinite of possible test cases to execute but the time and resource constraints are limited then some good selection method or algorithm is needed. The goal is to find a finite set of test cases that test the critical places where a failure is more likely to happen. This is a very complex problem and here an experienced tester that really knows and understands the system would rely on his or hers gods felling. The tester needs to be able to select test cases that both produce valid and invalid outputs and tests different parts of the system. There are also some informal methods such as boundary value testing that can help when choosing the right test cases.

Expected: To know if the result from the test is correct or not it is needed to know the expected output with a certain input. This problem is often called the oracle problem. An oracle is a person how can give wise counsel or even predict the future. In software testing the oracle have the expected output from the system depending on the input. The oracle problem can either be solved with manual inspections or using some automated process.

3.1 Objective of software testing

The main objective of testing software is to be sure that the software has as high quality as needed, all stated requirements on the system have been fulfilled and assurance that the system gives the output as intended on the given input.

3.2 Different kind of testing

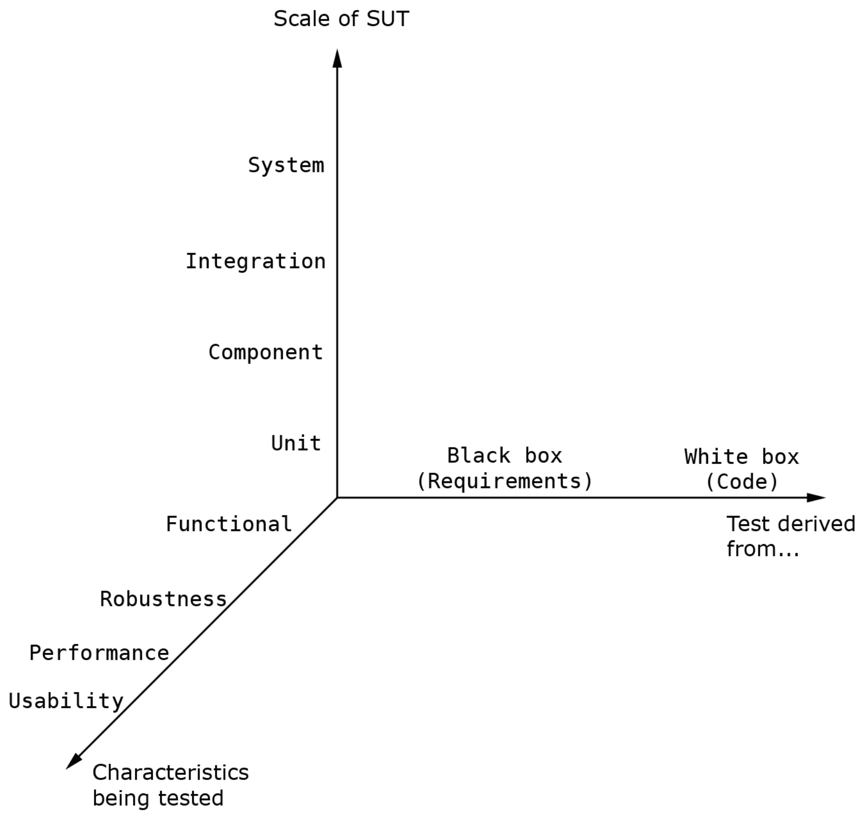


Figure 3.2.1 Different kind of testing

This picture shows a three axis view of different kind of testing. The vertical axis shows the scale of the System Under Test (SUT), from testing small units up to testing the whole system. The axis that goes horizontal shows which kind of information that is used when testing. The last axis which is going out of the book shows the different characteristics that are possible to test.

Finding bugs and fixing them in an early stage in the development process is an essential task if you want to do a successful story, with your product. Some authors and professors talk about multiplying the cost for finding and fixing a bug with 10 for each step upwards you go in the test process.

3.2.1 Unit test

Unit testing is a procedure for testing and validation of the smallest part in the software. It can be a single procedure or method in a class. Often this type of testing belongs to the programmer's tasks, because it is easy to verify a single unit while you are coding it.

3.2.2 Component testing

A component is built up by several units. Component testing performs testing on single components/subsystems without any communication between different subsystems to assure that the component is operating as it should.

3.2.3 Integration testing

In integration testing different components and subsystem are integrated and tested to see that they are working correctly together. Integration testing can expose problems with the interfaces between the different components.

3.2.4 System testing

System testing is the last testing step before the system is delivered to customer. In this step the whole system should be integrated and operating as intended. Finding mayor design mistakes in this step can jeopardize the outcome of the product. Of course it is better to find a bug in this step than not finding the bug at all, but it is desirable to find them in earlier stages of the test process.

3.2.5 White box testing

White box testing is also called structural- or glass-box testing in the literature. To be able to perform white box testing you need to have detailed knowledge of how the system is built. This testing technique requires complete access to the source code. The purpose of the tests is to verify the internal logic in the test object. Using white-box testing techniques the software engineer can derive test cases or a test suite that:

1. Executes all independent paths within the test objective at least on time
2. Executes all true and false paths in a logical decision
3. Executes all loops at values within the loop condition and boundary values
4. Exercise internal data structures to validate their validity.

3.2.6 Black box testing

In black box testing the object under test is viewed as a black box. You don't know the internal design of the object and you don't care about it. Your testing concern is what happens when you give the object some input stimuli and you test that the object responds to the stimuli in the correct way.

In black box testing the focus is on the requirements of the system. The derived test cases are therefore taken from the requirement specification.

3.2.7 Functional testing

The most common characteristics that are being tested is functional testing, also known as behavioral testing and in some literature even black box testing. The aim of functional testing is to find errors in the functionality of the system. You feed the system under test with input data and analyze the output.

3.2.8 Robustness testing

When you are doing robustness tests the main goal is to find errors when the system is in an abnormal state. For example when the system is given invalid input values, some part of the system is unavailable or some hardware or network failure. This testing ensures that the system can cope with situations even if everything is not normal.

3.2.9 Performance testing

During performance testing the system is tested with heavy load and is pushed to its limits. It demonstrates that the system meets the performance criteria and measure what parts of the system or workload cause the system to perform badly.

3.2.10 Usability testing

This testing method focuses on measuring and finding user interface problems, which may make the software difficult to use or may cause users to misinterpret the output. One way of performing this test is to observe people using the system to discover errors and areas of improvement potential.

4 Model-Based Testing

4.1 Introduction story

Before introducing what Model-Based Testing (MBT) is a story, that I have read in Practical Model-Based Testing by Mark Uttting and Bruno Legeards, illustrates the problem. This story does not come from the Computer Science world, but instead it is about the fish population in the New Zealand rivers and lakes.

The Koi Carp fish was accidently planted to the Auckland/Waikato region. This type of fish is not good for the rest of the ecosystem. It grows to a length of 75 cm, and eats everything that comes in its way just like a vacuum cleaner. Now imagine that you are the regional manager for some part of the river or a lake and your task is to prevent the Koi Carp from increasing its territory so that other fishes that is considered to be better species can live there. What will you do?

You have three different choices.

- Employ hundreds of amateur fishermen to fish with rods and hooks and offer a bounty payment for each Koi Carp caught.
- Place nets at strategic places, with regular inspections to kill all Koi Carp and release all other fish.
- Use an advanced technology solution, such as an electro fishing boat that attracts all fish and allows pest fish like Koi Carp to be killed while other fish can be returned to the water unharmed.

This story can easily be transferred to the Computer Science region. Just replace the river or lake with a software development project and the vicious Koi Carp with faults and bugs in the software. Then the three different choices will be.

- Employ a dozen full-time testers to manually design tests, record the tests on paper, and then manually perform the tests each time the system changes.
- Manually design a set of tests and then use automated test execution tools to rerun them after every change and report tests that fail.
- Use state-of-the-art tools that can automatically generate tests from a model of your requirements, can regenerate updates test suites each time the requirements change, and can report exactly which requirements have been tested and which have not.

If you believe that the third solution is the best one then maybe you should consider using model-based testing.

4.2 What is Model-Based Testing?

Model-based testing can be summarized in some short sentences.

> It is essentially a technique for automatic creation of test cases from a specified software model. The key advantage of this technique is that test generation can systematically derive all combination of tests associated with the requirements represented in the model to automate both the test design and test execution process.

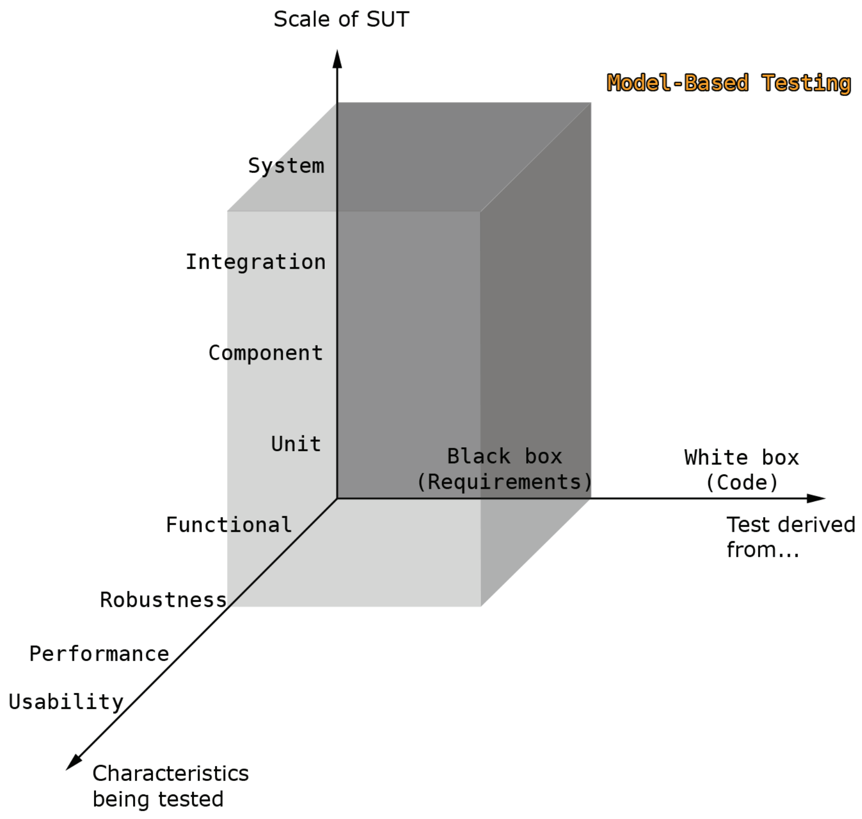


Figure 4.2.1 Model-Based Testing in the testing process

As you can see in this illustrative picture model-based testing (the box) is a functional testing technique and it is applicable to all levels of SUT testing. Model-based testing is a black-box testing technique for automation of tests. Normal black-box testing implies that you manually write the needed test cases based on the requirements specification and execute them manually. The difference with model-based testing is that you construct an abstract behavioral model of the SUT and from that model automatically generates test cases.

There are four different categories of model-based testing:

1. Generation of test input data from domain model
2. Generation of test cases from an environment model
3. Generation of test script from abstract tests

4. Generation of test cases with oracles from a behavior model

The first category of model-based testing is when you generate test input data from the domain model and you use smart selection and combinatorial algorithms so that you don't need to test the SUT with all combinations of input data but rather a minimal subset of the input data. This type of generation has it benefits, you get a good set of input data but you don't know whether or not a test has passed of failed.

The second approach with generation of test cases from an environment model is a bit different. The environmental model has information about statistics of the SUT environment; operation frequencies, data values distributions, etc. From this type of model it is possible to generate a sequence of calls to the SUT, but it is not possible to know if a test passed of failed because the sequence does not specify the expected output.

In the third type of model-based testing you don't provide a model but instead you provide abstract test descriptions, which can be Unified Markup Language (UML) sequence diagram or in some other type. With this approach the model focus on transforming these abstract sequences to more low-level test scripts that can be executed on the SUT. The model has information about the structure and API of the SUT.

The last approach generates executable test cases with input values and also includes oracle information for each test case. This method makes it therefore possible to totally automate the test case generation phase and the test execution phase. The model is a behavioral model of the system under test, behavioral model means that the model behaves like the SUT but the implementations is not totally accurate. The opposite of behavioral is structural and this is what is implemented in the SUT. This category of model-based testing is more sophisticated and complex than the other categories, but it has greater potential payback features. Most of the commercial tools that are available on the market implements feature from this approach.

4.3 The Model-Based Testing process

All testing processes involving functional testing needs to fulfill these four key features:

Designing the test cases: The requirements on the system must be analyzed so that the proper test cases can be created that test all requirements. Also test criteria for passing or failing a test must be addressed.

Executing the tests: The constructed test cases are executed on the system under test.

Analyzing the result: For each test case the system will produce an output. This output will be compared with the criteria from the design phase. A pass or fail will be the result on each test case.

Verifying how the tests cover the requirements: To assure the quality of the test process and the quality of the product the coverage must be measured. This can be done using a traceability matrix that lists each test case and which requirement it tests.

The general model-based testing flow can be illustrated like this:

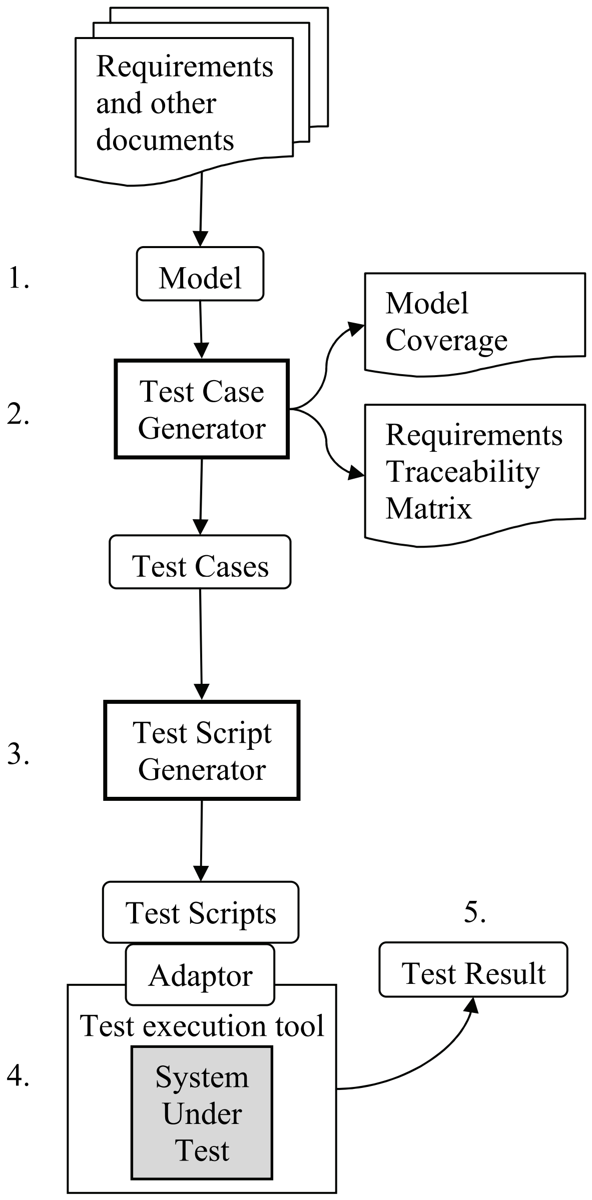


Figure 4.3.1 Model-Based Testing process

The first step in the model-based testing process is to write or design an abstract (behavioral) model of the system under test. This model is based on the specified requirements on the system. One difficult task is to build the model in the right detail level. It must have enough details so that good test cases can be generated but if the model is too detailed then it will be too complex. The abstract model should be smaller and simpler then the SUT and it should only focus on the things you want to test. There are various ways to produce the abstract model, some tools uses some textural language other uses some graphical notation like UML state machines or extended finite state machines. There can also be a mixture of both graphical and textural notation. A good tool should also be able do some model checking that analyzes to see if the model has any errors.

The second step is the generation of abstract test cases from the model. In this step the tool may need some guidance because there are almost an infinite number of different possible test cases. The guidance can be performed in different ways in different tools. Possible guidance criterion is which type of model coverage that should be used; all-states, all-transitions etc. Other possible guidance could be provided using use cases, all depending on the test generation tool.

A mature model-based testing tools should also provide reports on which requirements that a given test case tested and how much of the model that has been covered by the test suite. The requirements traceability matrix is a table with all test cases on one axis and all requirements on the other axis. If a test case covers a specific requirement then a mark is placed where the test case and requirement crosses each other in the table. The coverage report indicates which part of the model that has been tested or not tested. If some part of the model has not been tested then it may indicate that the model has some fault, perhaps this part of the model is statistical unreachable or the generation tool may need some more guidance to reach this region.

The generated test cases in the second step need to be changed or transformed into test cases that can be executed on the SUT. This is because the model is an abstract model (simplified) and does not have all the structural features that the SUT has.

The third step takes the abstract test cases and makes them testable on the real system. This step involves creating (or using existing) adapters that wrap around the SUT and transforms each abstract instruction into executable instructions. The main advantage of having two separate layers is that the abstract tests are not dependent on a specific test environment. If the test needs to be executed in a different environment then the only change that is needed is to change the adapter code.

The fourth step is the execution phase. The execution is done on the SUT itself or an accurate SUT simulator. This step is always performed regardless of which type of testing method that is used.

The fifth step is where the output of the tests is analyzed. Even this step is a normal step for all type of testing techniques. Each test that reports a failure needs to be examined so that the fault is located. In a manual test process the fault is often caused either by the test case or the SUT or badly written requirements. When the MBT process is used then the area of where the fault may be located is increased. It can be in the model or it can be in the adapter code.

4.4 Benefits with Model-Based Testing

If you asked someone what the benefits with model-based testing is almost everyone would say that the automatic generation of test cases is the main benefit. This is absolutely true, but MBT gives much more to the testing process.

4.4.1 Comprehensive tests

The test case generation tool traverse the model in a very thorough way and this implies that the many test cases that are hard to come up with using manually testing can be created with

MBT. Model-based testing tools often have features so that it tries to test boundary values, where statistically many faults often occur.

4.4.2 Time reduction

Testing with the model-based testing approach can lead to time reduction if the time to write and maintain the model when generating the test cases is smaller than the time for manually creating the test cases and maintaining them. Introducing a new method into the organization takes time and this has to be taken into account when measuring time.

4.4.3 Finding requirement defects

In the first step of the model-based testing process the behavioral model is produced. This model makes it possible to find omissions, contradictions and unclear requirements. If something is unclear when making the model then it must be address and clarified to make the work proceed with building the model. The model is built in an early stage and therefore the requirements are examined in an early stage. Model-based testing also helps finding undiscovered requirements that has not been put into a requirement yet.

Finding a faulty requirement in an early development phase is a very good thing, it is time saving and cost saving and also makes it possible to design a better system. You don't have to do patch fixing in the end of the project.

One long-term effect of model-based testing might be to change the roll of the testers. Instead of catching errors in the end of the project they catch them in an early phase.

4.4.4 Requirements evolution

As the project is proceeding the requirements may change. If manual testing is used then all the created test cases must be analyzed and verified. When the requirements change it can affect the test cases. In model-based testing on the other hand the only change needed is the change of the model and then regenerating the automatic test case generation. Since the model is often much smaller than the test suite than this process is less time consuming.

4.4.5 Requirement validation

A model serves as a unifying point of reference that all teams and individuals involved in the development process can share, reuse and benefit from. The model could be of use for others than just the testers. Maybe designers and testers should collaborate when the model is produced. A picture (model) says more than a thousand words, is an old saying. This is true with models too. People tend to find it easier to understand things if there are picturized.

4.4.6 Traceability

Traceability means that it is possible to relate a requirement to the model and a certain test case to the model and the requirement specification. The traceability helps when you should justify why a specific test case was generated from the model and what requirements have been tested. It also helps when the model evolves and grows in size, because it enables tracing for new test cases that belong to the new feature or modification added.

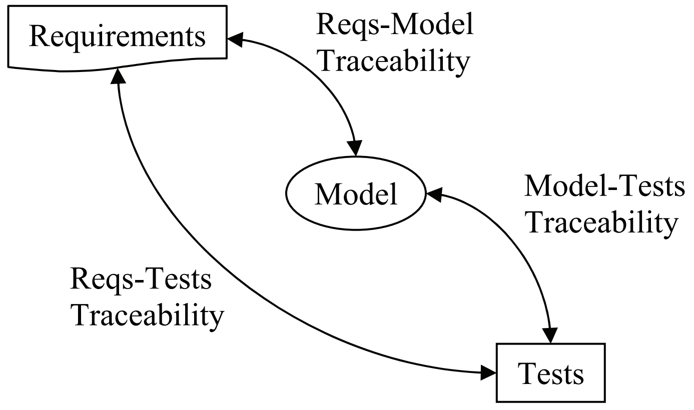


Figure 4.4.1 Traceability

There are three different types of traceability as seen in the picture; *Req-Model traceability* is used to analyze which requirements are not yet in the model or how does a requirement influence the model. *Model-Tests traceability* is used to visualize a given test case as a sequence of transitions in the model or showing which transitions in the model that have not been covered by any test case. To perform this trace the tool needs to record each transition it takes and in which order. The last traceability aspect is *Req-Test traceability* and this shows how a given requirement is tested in a given test case. This trace is the least technical approach and it can be used either by the test engineer or by some nontechnical person. It identifies requirements that have not been tested and show all tests that relate to a given requirement.

4.5 Drawbacks with Model-Based Testing

Nothing comes for free. There is no such thing as a free lunch, you always pay it in some way. Model-based testing is no exception in this matter. Skills, time and other resources need to be allocated for making preparations, overcoming common difficulties and working around the major drawbacks. Model-based testing is not suitable for everyone and every development process, there are no silver bullets or "complete" testing methods.

4.5.1 Testing skills

Model-based testing demands certain skills of the testers. They need to be familiar with or able to adapt to the model based thinking and its underlying supporting mathematics and theories. For example if the models are made with finite state machines then the tester needs to know how to produce such a model with its formal language, automata theory and perhaps some graph theory. Testers also need to have knowledge about model-based tools, scripts and programming language necessary to complete the task.

4.5.2 Splitting and merging models

In development project with more than two persons, it is often needed to split the development task into more than one piece. Otherwise you will not use your appointed resources in an efficient way. Splitting and merging is something that you need to do in almost every divide and conquer development processes. This is not something that is special for model-based testing, you have this problem in all type of larger development but when using models as in model-based testing you have to do it here also. So that will be one extra time when using model-based testing, compared with manual testing where you only need to split the structural model.

4.5.3 State space explosion

State space explosion is a big issue for all model based approaches, not only for model-based testing but also for model-based design etc. The thing that is meant when talking about state space explosion is the problem when models begin to grow in size, or more precisely grow in states. State space explosion makes model maintenance, checking, reviewing, nonrandom test generation and achieving coverage criteria more difficult and more time consuming.

Fortunately there are ways to address this problem. The key thing to do is abstraction and exclusion. Abstraction is that you group things that belong together into one state. For example if you are building a model with multiple input fields and an OK button. You could model it so that each input field can have valid or invalid data or you can model it with abstraction and group all fields together and only have valid or invalid data for all fields together. Of course you lose information by doing so but the state space will be much smaller. The other way is to simply cut off, exclude, information from the model. You then need to test the excluded information in some other way, but your model has been made simpler. There is always a trade of when simplifying.

4.5.4 Time to analyze failed tests

When one of the generated tests fails, then we need to decide where to look for the failure. There are three possible places to examine. It can be in the SUT itself, the adaptor code that connects the abstract test case to the SUT or there can be an error in the model. In manual testing the fault can only be in the SUT or the test script so it is less places to investigate with manual testing. The generated test case from the model-based testing may also be more complex and less intuitive than then test case created by hand, so it may take longer time to find the cause of the failure.

4.5.5 Others

The issues that are pointed out in this section are problems that are not really specific for model-based testing, but it is essential to bring them up for preventive reasons.

During the development process of a product, it may happen that requirements will be changed. If the model is built using these *outdated requirements* then the model and the SUT will not be the same and many faults will be found. These faults are not real faults, and a working process to prevent this situation is needed.

All parts of a SUT are not suitable for model-based testing. *Inappropriate use of model-based testing* does not give any extra value to the product, it is only a waste of resources. If it is much easier to build test cases for a specific part by hand, then you should do it by hand. One risk here is that it takes experience to know which part should be modeled with model-based testing and which part should be tested manually.

5 Constructing a model

The most important step in modeling is to select the right abstraction level of the model. The model needs to be accurate so that interesting test cases can be generated but it should not be as accurate as the SUT itself. If it is to precise then it will take too much effort to produce the model, the test generation step will be time consuming or taking infinite time and the test cases generated may not be the one that was expected or wanted. It is a good chance that the generated test cases will be on the wrong detail level.

To choose the right abstract level of a model is a very challenging task it will need practical experience as many other things in life.

5.1 Model guidelines

- Try to separate different types of functionality to different subsystems, rather than building the entire model in just one huge and complex model.

- Test each subsystem independently if it is possible before merging it into the full scale model. This will help when finding smaller errors in the model.

- Only include features, operations and data fields that you really need to meet the test objectives.

- Focus on the behavioral of the SUT, not the test cases that you want to produce. If you focus on the test cases you will only be able to generate these test cases with the tool, you may miss some interesting test cases that the tool would have found if the focus had been on the SUT. It is the tester's task to design the behavioral model of the SUT and the generation tool is responsible for finding interesting test cases. Not the other way around.

- Try to simplify complex operations with simpler structures like enumeration of the possible values.

- Consider the interface, with input and output parameters, of the model in a very early stage of the development phase. The interface detail level indicates the abstraction level of the model.

- Build the model in an iterative way. Don't address all problems at once. Add functionality and test it to insure its correctness.

- Let other testers view and examine your model.

Selection input and output parameters are essential when building the model. If an input parameter changes some operation in the SUT and you want to test this change, then this input parameter should be in your model. Otherwise it is better to omit this input parameter to decrease the complexity. Using less input parameters will probably help the generation tool to generate good test cases, and also making the generation time smaller. This is because when using a smaller amount of input parameters then the combinatorial problem in selecting input values will be easier for the test case generation tool.

5.2 Different model notations

There are a lot of different notations in how you can model your system. Different modeling tools use different notations and these notations have varying functionality. Some of the groups of notation that exist will be described here.

5.2.1 Data-flow notations

Data-flow notations focus on the how data are moved around the SUT. How the data are transformed from one type to another and how it is stored. A typical data-flow notation is the block diagram notation in Matlab Simulink.

5.2.2 Functional notations

These notations describe the system as a set of mathematical functions. There are two different approaches algebraic specification and higher-order functions. In the algebraic approach functions are grouped by object types that appear in their domain. Then desired properties are specified as conditional equations that capture the functionality. This approach is hard to use because it quickly gets very complicated, so it is not used so much in MBT. In the other approach, higher-order functions, the functions are grouped into logical theories. These theories contain axioms defining the various functions and variable declarations. One model-based tool that uses functional notation with higher-order functions is UPPAAL. UPPAAL is collaboration between Uppsala University and Aalborg University and it is an environment for modeling, simulation and verification of real-time system with critical time constraints.

5.2.3 History-based notations

The principle here is to describe the allowable traces or paths of the modeled systems over time. The notation of time is important and can be described in various ways. Time can be linear or branching. Time structures can be discrete or continuous. The properties may refer to time points, time intervals or both.

Message sequence charts (MSC) is a graphical and textual language for the description and specification of the interactions between system components. The main area of application for MSC is as an overview specification of the communication behavior of real-time systems. It is good for visually showing interactions among components, but not so good at specifying the detailed behavior of each component. Therefore it is sometimes used for showing the generated test cases from a model-based testing tool. MSC exist in UML as well but is called sequence diagrams in UML.

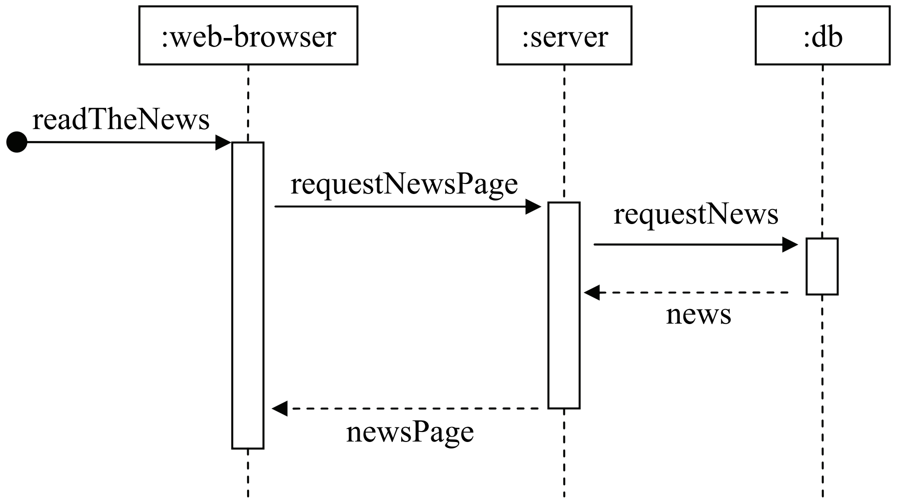


Figure 5.2.1 Message sequence chart (MSC)

5.2.4 Operational notations

This type of notation describes the system as a collection of processes that can be executing in parallel. The notation is particularly suited to describing distributed systems and communications protocol.

Petri net is one of the available notations in this group, it was invented by Carl Adam Petri in 1962. A Petri net consists of places (unfilled circles), transitions (filled rectangles) and directed arcs and tokens (filled circles). Each place can hold a number of tokens and when a token moves from a place to another place it travels through a transition and executes the process or operation that belong to that transition. A movement of one or more tokens is called a firing.

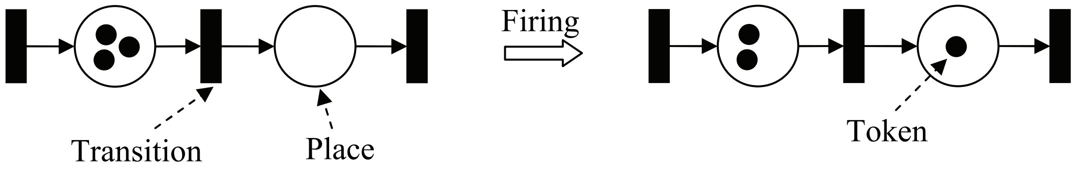


Figure 5.2.2 Petri net

5.2.5 State-based (pre/post) notations

Instead of describing what happens at a specific time, as in history-based notations, state-based notations describes the allowable states in a system at some point of time. The system is modeled with a collection of variables, which represent the internal states of the system plus some operations that modify these variables. Objects in an object oriented language have much in common with these variables. Some state-based or pre/post notations are the UML Object Constraint Language (OCL), Java Modeling Language, Z or B abstract machine notation.

State-based notations are also called pre/post notations. The precondition specifies what type of input data that is valid and constraints on them. The post condition handles the data manipulation, which is an abstraction of how it is changed in the SUT.

Pre/post Coffee machine example with the B notation:

```
MACHINE
   CoffeeMachine                           // Name of the machine
VARIABLES
   balance, limit                          // Variables
INVARIANT
   limit : INT & balance : INT &           // Constraints on the variables
   0 <= balance & balance <= limit
INITITALISATION
   balance := 0 || limit := 10             // Initial values
OPERATIONS
   reject <-- insertCoin(coin) =
          PRE coin : { 1, 5, 10 }          // PRECONDITION
          THEN
          IF coin + balance <= limit
          THEN
                 balance := balance + coin ||
                 reject := 0
          ELSE
                 reject := coin
          END
   END;

   money <-- returnButton =
          money := balance || balance := 0
END
```

The operations part of the code is where the real action takes place. `reject <-- insertCoin(coin)` says that coin is an input parameter to the function insertCoin and reject is the output parameter. Coin can only be 1, 5 or 10 which is specified in the precondition. The rest of the lines in the function belong to the post condition. The `money := balance || balance := 0` says that these two statements will be executed in parallel (concurrent). The variable money will have the value of balance and balance will be set to zero, but money will not be zero it will have the value before balance was set to zero. This can be confusing at first if you are only familiar with sequential programming.

5.2.6 Statistical notations

These notations model a system by a probabilistic model of the events and input values. The use of Markov chains is one model that is often used. If a model has the Markov chain properties then many statistical features are easily received from the model. The main property that must be fulfilled is that the next state in the model is not depending on any previous states. The model should not remember previous steps when deciding the next step.

Statistical notations are good for specifying distributions of events and driving the choice of test sequences and inputs for the SUT but are generally weak at predicting the expected output, so it is not usually possible to automatically generate oracle information during test case generation.

5.2.7 Transition-based notations

This type of notation describes the system as a state machine with actions performed when it takes a transition from one state to another. Typically, they are graphical node-and-arc notations, such as a Finite State Machine (FSM). The properties of interest are specified by a set of transition functions in the state machine. These functions specify when a transition should be triggered, what properties must be fulfilled to take the transition and what action should be performed when the transition is taken.

Transition-based notations don't have to be in graphical form, they can be in textural or tabular form as well. But the graphical notations are more often used and some of them are UML State Machines, STATEMATE, state charts and Simulink Stateflow charts.

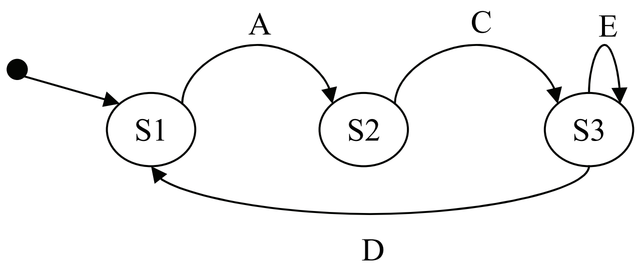


Figure 5.2.3 Simple finite state machine

6 Test case generation

This chapter will describe which opportunities you have in controlling the automated test case generation. It is your model-based testing tool that generates the test cases but you have the possibility to guide the tool by selection which type of criteria the generation should use. Different tools have different test selection criteria and often only a subset of all criteria's that will be presented in this chapter.

It is good to remember that MBT is a black-box testing technique and that the coverage criteria represented here will only measure how well the generated test suite covers the model. It is not possible to measure source code coverage of the SUT or coverage measurements made on the SUT. This does not necessary have to be a negative thing though, it gives the opportunity to start generating test cases using some test criteria before the actual coding of the SUT has begun.

The real measurement of statement and branch coverage can be done when the SUT is executed with the generated test cases.

The choice of coverage criteria determines which type of algorithms that will be used by the model-based testing tool for generating the tests, how large the test suite will be, how long time it will take to generate them and which parts of the model that will be tested. When applying a coverage criterion you are saying to the tool "please try and generate a test suite that fulfills this criterion". Maybe you are requesting for something that is very hard or even impossible to solve. The tool will not perform any black magic for you, it is working in a restricted domain and will do its best in accomplishing your request. A point of failing can be that some part of the model is statistical unreachable and therefore it is not possible to accomplish the criteria. There is also a possibility that the tool is not powerful enough to find a path in the model so that the criteria can be achieved to 100 percent coverage. In the case of failing criteria the tool should be able to generate some type of report that indicates which part that could not be covered so that it can be investigated more thorough.

6.1 Structural model coverage criteria

Structural model coverage has some similarities with code based coverage criteria that can be used in white-box testing. The similarities are the control-flow and the data-flow coverage criteria, but there is more that belongs to the structural model coverage genre like transition-based and UML-based coverage criteria.

6.1.1 Control-flow

Control-flow coverage covers criteria as statements, branches, loops and paths in the model code. The picture below shows the different categories of control-flow coverage criteria that will be represented here.

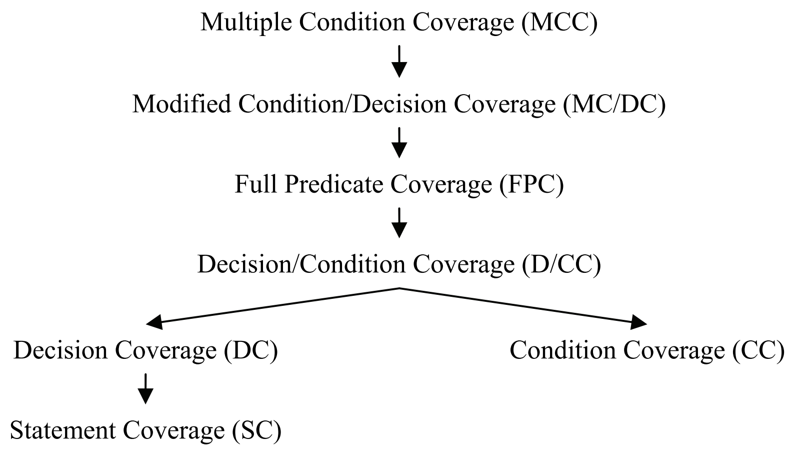

Multiple Condition Coverage (MCC)
Modified Condition/Decision Coverage (MC/DC)
Full Predicate Coverage (FPC)
Decision/Condition Coverage (D/CC)
Decision Coverage (DC)
Condition Coverage (CC)
Statement Coverage (SC)

Figure 6.1.1 Control-flow hierarchy

Criteria higher up in the hierarchy are stronger and acquire the lower criterion to be true. The lower criterion is a subset of the higher criterion.

6.1.1.1 Statement coverage (SC)

The test suite must cover all reachable statements in the model. All if-statements, loop-statements should be executed at least one time, but it is not required to test the true and the false path of the decision.

6.1.1.2 Decision coverage (DC)

The test suite executes all true and false branches of every reachable decision in the model. A decision or branch can be an if-statement or a conditional loop-statement. To satisfy decision coverage a test suite must satisfy statement coverage as well, so decision coverage is a stronger criterion. Decision coverage is also called branch coverage in some literature.

A clarifying example:

```
if (condition1 && (condition2 || function1()))
    statement1;
else
    statement2;
```

100 percent branch coverage could be achieved with these two test cases:

- `condition1 == true` and `condition2 == true`
- `condition1 == false`

6.1.1.3 Condition coverage (CC)

To achieve condition coverage at 100 percent every Boolean condition must have the true and false value in some test case. Using the same example as in decision coverage the test suite could look like this:

- `condition1 == true` and `condition2 == true` and `function1() == true`

- `condition1 == false` and `condition2 == false` and `function1() == false`

For any decision regardless how many Boolean conditions it has it will be needed two test cases. One when every condition is true and one when every condition is false. This is theoretically speaking, in practice it may need a lot more test cases because the conditions may depend on each other.

6.1.1.4 Decision/condition coverage (D/CC)

When a test suite covers both decision and condition coverage, it is in this category.

6.1.1.5 Full predicate coverage (FPC)

Full prediction coverage is based on the philosophy that all conditions in an expression should be tested independently. A condition is a Boolean expression that does not contain any AND, OR and NOT operators. A Boolean variable is an example of a condition. A test set fulfills FPC if each condition in the model is forced to true and to false and the condition is directly correlated with the outcome of the decision. A condition `c` is directly correlated with the decision `d` if one of these two situations occurs, `d⇔c` or `d⇔not(c)`. Both the condition and the decision must have the same outcome or they must have the opposite outcome.

For example this set is not allowed.

`c == true → d == true` and `c == false → d == true`. Because neither `d⇔c` nor `d⇔not(c)` is true in this cause. The decision will be true regardless of what `c` is.

6.1.1.6 Modified condition/decision coverage (MC/DC)

This control coverage criterion strengthens the directly correlated requirements of full prediction coverage by saying that each condition `c` should independently affect the outcome of the decision `d`. This coverage is achieved by holding all conditions fixed in a decision except the condition `c` that is tested for the moment. If there are N conditions in a decision then it is needed a maximum of 2N tests on the decision for totally covering MC/DC.

Clarifying example showing that maximum 2N tests are needed and enough (not a proof):

```
condition1 && (condition2 || condition3)
```

Let's say that we want to test `condition1` then we will hold the other two conditions fixed (one of the conditions on the right side of the `&&` operator must be true to fulfill MC/DC). The `condition1` can be true or false, so there will be two tests when testing `condition1`. But because of the `&&` operator `condition1` must be true when testing the right side of the `&&`.

Condition1	*Condition2*	*Condition3*
true	true	false
false	true	false
true	false	false
true	false	true

Table 6.1.1 Test pattern for fulfilling MC/DC

The first and second tests test `condition1`, first and third test `condtion2`, and `condition3` is tested with the third and fourth.

6.1.1.7 Multiple condition coverage (MCC)

To achieve multiple condition coverage the test suite needs to exercise all possible combinations of each decision and its conditions. It is very hard to perform this in practice because a decision with N conditions needs to have 2^N different tests. This is because each condition needs to be tested with true and with false with all different combinations of the other conditions. It can be questioned if this coverage criterion adds something important to the test suite. It can do it if it is hard to find distinct good test, because all possible combinations will be tested. But is there really the time for doing this type of testing? Many of the test cases will not lead to anything, because of the operators. The example below shows this. The exponential growth of the tests need also makes it impossible to fulfill MCC if there are many conditions.

Example:

The same decision as before will be used.

```
condition1 && (condition2 || condition3)
```

It has three conditions so eight tests are needed, the table show each of them.

Condition1	Condition2	Condition3
true	true	true
true	true	false
true	false	true
true	false	false
false	true	true
false	true	false
false	false	true
false	false	false

Table 6.1.2 Test pattern for MCC

All of these tests will not produce any different result. The first, second and third will return the same result. The last four will also return the same result, because `condition1 == false` and then the value of `condition2` and `condition3` will not do any difference.

As you can see many of the test cases will not produce any new result, if your task is not to test the Boolean operators then all tests could be good test cases.

6.1.2 Data-Flow

Data-flow-oriented coverage criteria cover read and writes to variables. A definition of a variable is a statement that sets the value of the variable (a write operation) and a use of a variable is an expression that uses the value of the variable (a read operation).

Some definitions are needed, `v` is a variable, `Dv` is when a write operation is performed on `v` and `Uv` is when a read is performed on the variable `v`. A path from `Dv` to `Uv` that does not contain any other definitions on `v` is called def-use pair and is denoted `(Dv, Uv)`. This definition ensures that the variable `v` has not been changed when it is read by `Uv`. A def-use pair is feasible if there is a test path from `Dv` to `Uv`, otherwise it is infeasible.

$$\begin{tikzcd}
\text{All-definition-use-paths} \arrow[d] \\
\text{All-uses} \arrow[d] \\
\text{All-definitions}
\end{tikzcd}$$

Figure 6.1.2 Data-flow hierarchy

6.1.2.1 All-definitions

This is the weakest data-flow coverage. It requires that the test suite tests at least one def-use pair `(Dv, Uv)` for every definition `Dv`. One path is enough. Easier said all write operations should have read operation and when the read is performed the value should not have changed from when the write was done.

$$\begin{tikzcd}
\mathrm{Dv1a} \arrow[d] & & \mathrm{Dv1b} & \\
\mathrm{Uv1a} & \mathrm{Uv1b} & \mathrm{Uv1c} & \mathrm{Uv1d}
\end{tikzcd}$$

Figure 6.1.3 All-definitions example

6.1.2.2 All-uses

This coverage extends the all-definitions. Now all uses of a variable should be tested.

$$\begin{tikzcd}
\mathrm{Dv1a} \arrow[d] \arrow[dr] \arrow[drr] \arrow[drrr] & & \mathrm{Dv1b} & \\
\mathrm{Uv1a} & \mathrm{Uv1b} & \mathrm{Uv1c} & \mathrm{Uv1d}
\end{tikzcd}$$

Figure 6.1.4 All-uses example

6.1.2.3 All-definition-use-paths

This is the strongest coverage of data-flow coverage. All feasible paths from all `Dv` to all `Uv` should be tested. This coverage usually requires too many test cases because there will be too many combinations.

$$\begin{tikzcd}
\mathrm{Dv1a} \arrow[d] \arrow[dr] \arrow[drr] \arrow[drrr] & & \mathrm{Dv1b} \arrow[dll] \arrow[dl] \arrow[d] \arrow[dr] & \\
\mathrm{Uv1a} & \mathrm{Uv1b} & \mathrm{Uv1c} & \mathrm{Uv1d}
\end{tikzcd}$$

Figure 6.1.5 All-definition-use-paths example

6.1.3 Transition-Based

In this section the most common model-based testing coverage for transition-based coverage will be presented and it will be explained how they relate to each other. Transition-based models are built using states and transitions, in some notations like state charts it is possible to have hierarchies with states, so that one state can hold other states inside itself.

To exemplify transition coverage criteria two models will be used. One is a state chart and one is a normal finite state machine (FSM).

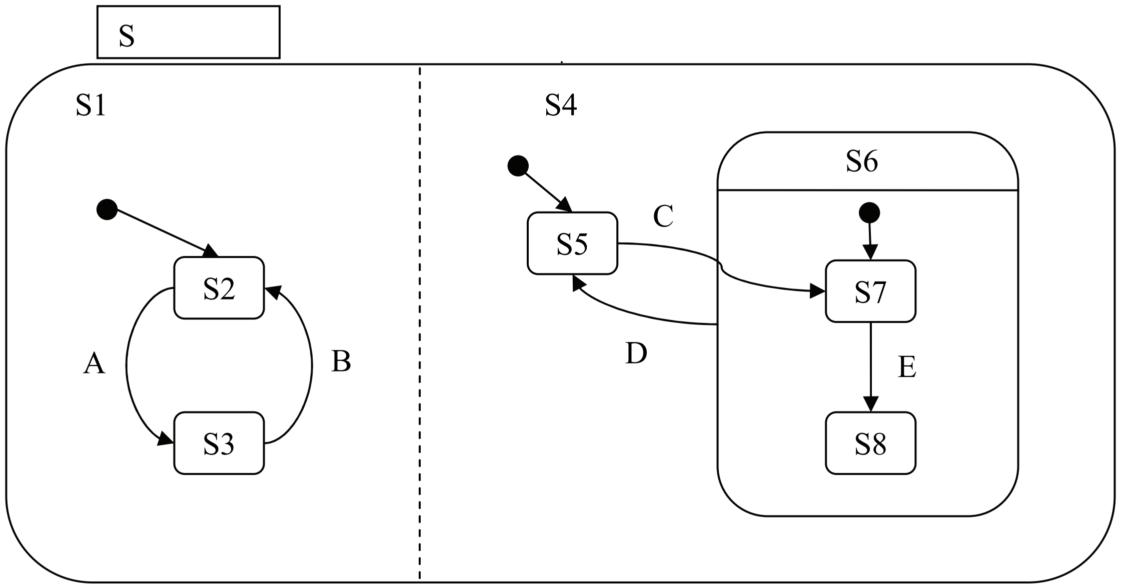


Figure 6.1.6 State chart

For a state chart there is something called configuration. A configuration is a snapshot of the state chart at some time. The configuration tells in which states the model is currently in. Because there can be parallelism and hierarchies in the state chart the configuration is made by enumerating all states it is in for that moment. It can for example be when the state chart is in the state {S, S1, S2, S4, S6, S8} and if the D transition is taken the configuration will change to {S, S1, S2, S4, S5} instead.

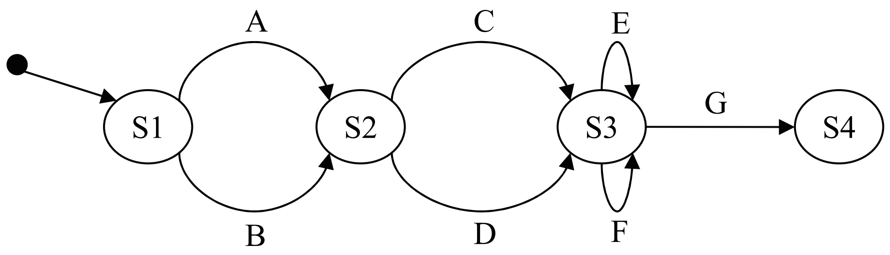


Figure 6.1.7 Finite state machine

If the below transitions-based coverage are applied to models with state variables and guards on the transition then it is usual to restrict the allowed paths to only paths that are reachable. This is because you don't want the coverage measurement to measure paths that are impossible to reach.

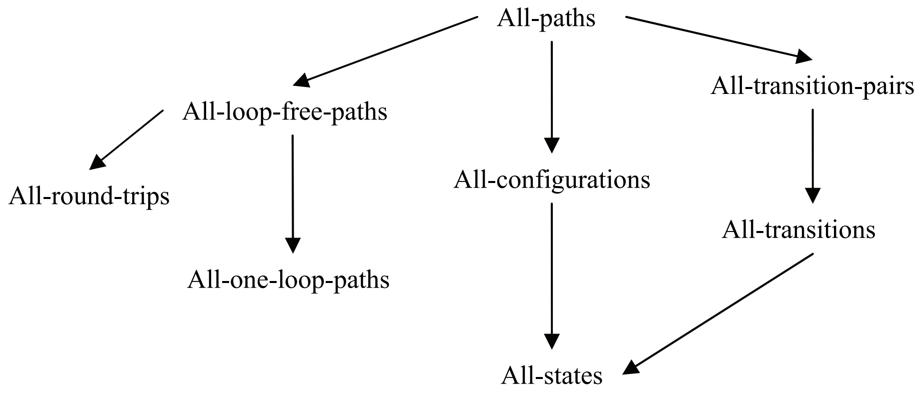


Figure 6.1.8 Transition hierarchy

6.1.3.1 All-states coverage

This coverage ensures that all states in a model have been visited at least once. To cover all-states in the FSM in Figure 6.1.7 a possible path can be B;D;G and to cover it in the state chart in Figure 6.1.6 these transitions A;C;E would be enough. This is because it will start in S2 (and S1) and S5 (and S4) simultaneously. By taking the A transition state S3 will be covered and when C is taken then S7 (and S6) is reached. The last transition E covers state S8 and now all states are covered.

6.1.3.2 All-configurations coverage

In this coverage measurement all configurations in the model must be covered at least once. If the model does not have any parallelism then this coverage criteria is the same as all-states coverage.

For the state chart Figure 6.1.6 this coverage can be achieved by traversing the model in this order C;E;A;D;C. There are 6 possible configurations because. It is calculated by multiplying the number of states in each parallel state machine. Only the inner states are counted. The left state machine has two inner states, namely {S2, S3} and the right has three {S5, S7, S8}. So the possible configurations are 2*3=6.

6.1.3.3 All-transitions coverage

In all-transition coverage the thing of interest is not states as in the two previous coverage criteria but instead transitions. As the name indicates all transitions in the model must be taken at least once.

To achieve this in the FSM model in Figure 6.1.7 these two traversations are possible A;C;E;G and B;D;F.

To achieve the same thing with the state chart in Figure 6.1.6 is ambiguous. It depends on how the interpretation is done. There is no real "right" interpretation of the D transition. Is it enough only to take the D transition from one of S7 or S8 or should the D transition be like two transitions one from S7 and one from S8? Different tools interpret it differently and you need to find out which interpretation is used.

6.1.3.4 All-transition-pairs coverage

The all-transition-pairs coverage says that all incoming transitions must be tested together with all outgoing transitions in a state. For example in state S3 in Figure 6.1.7 there are two incoming and three outgoing so there will be six (2*3=6) combinations, namely C;E, C;F, C;G, D;E, D;F and D;G.

6.1.3.5 All-loop-free-paths coverage

This coverage criterion ensures that all loop free paths are covered. A loop free path is a path that does not contain repetition of any configuration. The FSM model in Figure 6.1.7 has four different configurations, one for each state. To achieve all-loop-free-paths these tests are needed A;C;G, A;D;G, B;C,G and B;D;G. Transition E and F can't be taken because this would result in a configuration state that has already been reached because it is a loop back to a previous state.

It is possible that some states in the model will not be reached when using all-loop-free-paths, for example if the F transition leads to a state, say S5, and then a transition H leads back to state S3. Then the state S5 nor transition H would be reached or walked.

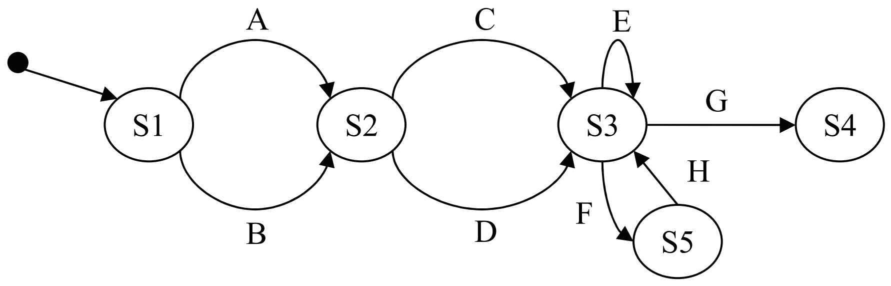


Figure 6.1.9 All-loop-free-paths example

6.1.3.6 All-one-loop-paths coverage

The all-one-loop-paths coverage is fulfilled when all loop-free paths have been taken and all paths that loop once. A more precise definition is, every path contains at most two repetitions of one (and only one) configuration.

For the FSM in Figure 6.1.7 the required test paths will be a combinations of A,B,C,D as in all-loop-free-paths. In state S3 it will take either E or F or none of them before taking G. For example A;D;E;G or A;D;G.

6.1.3.7 All-round-trips coverage

This coverage criterion is similar to all-one-loop-paths in some sense. It requires that all loops are tested in the model, but it is weaker because it only requires one path for testing the loop. In all-one-loop-paths it is required that all paths for a loop are covered. By having the all-round-trips in this way it is much easier to accomplish this criterion in practice. Because it will be a linear among of test cases needed.

For testing the FSM model in Figure 6.1.7 with all-round-trips coverage it is only required to test it with these two test paths A;C;E;G and B;D;F. All loops have been visited and all transitions have been taken. So the criteria are fulfilled.

6.1.3.8 All-paths coverage

All possible paths must be covered in all-paths coverage. In the FSM model in Figure 6.1.7 it will be an infinite number of test paths, because it is possible to loop forever on the E or F when you are in state S3. This criterion is only suited for small models without any loops or with some boundary on how many loops to cover.

6.1.4 UML-Based

The UML language is for specifying, visualizing, constructing and documenting the artifacts of the software system. UML provides a variety of diagrams that can be used to present different views of an object oriented (OO) system at different stages of the development life cycle. A lot of the coverage criteria that has been presented in previous sections of this chapter are also suitable for UML-based coverage criteria, for example decision and transition coverage can be used on UML state machines.

Only new coverage criteria that have not been mentioned in earlier sections will be described here.

6.1.4.1 Class Diagram

A class diagram shows the static structure of a system. It identifies all the entities, along with their attributes and how the entities in the system relate to each other. These relationships or associations are represented by links among the entities. The links can have ranges specified on each end. For example if a link has 1 on one of the ends and 5 on the other, then it means that the entity with 1 can have 5 entities of the other type.

6.1.4.1.1 Association-end multiplicity (AEM) coverage

This coverage method is fulfilled if and only if it exist a test case that causes each representative multiplicity-pair to be created.

Example:
There exist a class A and a class B. There is an association between A and B. The range on the A side is 1..1, meaning that B can only have one instance of A. On the B side of the association there is a range of 0..5, meaning that A can have 0 to 5 instances of B.

One strategy to get the multiplicity-pair is to partition the equivalence into groups and doing so for each class. Class A only has one equivalence class, namely {1}. Class B has three equivalence classes {0}, 1..4 and {5}. The combination of the all equivalence classes of A and B will give the multiplicity-pairs: (1,0), (1,2) and (1,5). In the second pair the 2 could be 1, 2, 3 or 4 it does not matter.

6.1.4.1.2 Generalization (GN) coverage

Generalization is typically implemented as inheritance. Inheritance is one of the main features of an object oriented language. One class can be the parent (generalization) to some other classes which are children (specializations). E.g. the parent class is Vehicle and a child to this parent could be Car, Motorcycle or Bike. To be able to cover this coverage criterion it is needed that all specializations in all generalizations are created at least once.

6.1.4.1.3 Class attribute (CA) coverage

This coverage criterion assures that a set of possible values for each attribute in a class is tested, all combinations of these values should be tested. The possible values can be all combinations of valid attribute values or a subset of them. If it is a subset then some good selection method is needed for selecting a good partition of attribute values.

6.2 Data coverage criteria

The valid input range of data to a system is often very large, and even if it is not so large then it quickly leads to a combinatorial explosion if all combinations of values should be tested. Data coverage criteria are useful for selecting a good set of few data values to use as input to the system.

Let's image that we have this easy example:

x: 0..99
y: 0..19

Condition: x > 50 and y > 10

Figure 6.2.1 Easy data coverage example

Without any data coverage criteria then all combinations need to be tested. The number of combinations will be 100*20 = 2000 different test cases. Is this really needed?

6.2.1 Boundary value testing

The idea with boundary value testing is straightforward, it is often more likely to find a fault near a boundary then if you just select some value in the range. E.g. x values in Figure 6.2.1 from 0 to 49 (50) belongs to the same equivalence group so there is really no need to test more than one of the values in this region.

This integer example will be used to illustrate the boundary value testing coverage's.

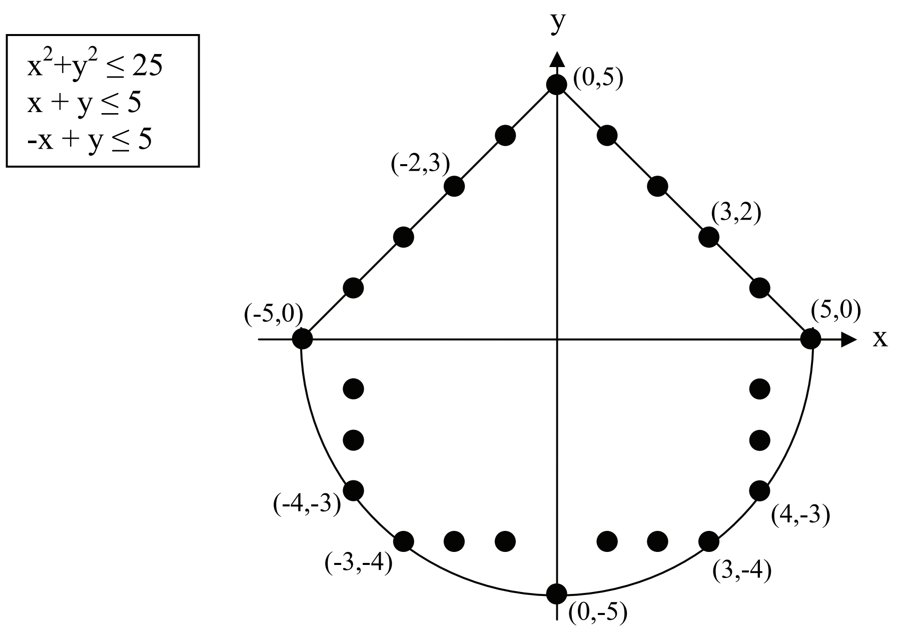


Figure 6.2.2 Integer example of boundary points of a shape

Four different type of boundary value testing will be presented, the hierarchy between them are as the picture below shows. A coverage method that is higher up in the tree is stronger than a coverage method lower done in the tree.

$$\begin{tikzcd}
 & & \text{All-boundaries Coverage} \arrow[d] \\
\text{All-edges Coverage} \arrow[dr] & & \text{Multidimensional-boundaries Coverage} \arrow[dl] \\
 & \text{One-boundary Coverage} &
\end{tikzcd}$$

Figure 6.2.3 Boundary value testing hierarchy

6.2.1.1 All-boundaries coverage

The all-boundaries coverage criterion is the strongest boundary value criterion. It acquires that all boundary value point is tested. This is often not realistic in a larger system where there are many conditions and with complex boundaries. But in Figure 6.2.2 this would not be impossible because there are only 24 boundary value points.

6.2.1.2 Multidimensional-boundaries coverage

For a test suite to satisfy this coverage method it is needed that every variable is assigned its minimum value and maximum value at least once. In Figure 6.2.2 this can be done by choosing the boundary value points: (-5,0), (0,5), (5,0), (0,-5). Instead of making 24 test cases as in all-boundaries coverage, this coverage method only needs 4 test cases in this specific example.

6.2.1.3 All-edges coverage

In all-edges coverage the decision is broken down to its conditions. E.g. Figure 6.2.2 have three conditions namely $x^2+y^2 \leq 25$, $x + y \leq 5$ and $-x + y \leq 5$. Each of these conditions defines an edge in the shape. To fulfill all-edges coverage at least one boundary point from each edge must be tested. This can be achieved with the points (0,5) and (3,-4). There are lots of different combinations to fulfill the coverage in this example.

6.2.1.4 One-boundary coverage

This boundary coverage is the weakest criterion, it only requires that some boundary value point is tested. Only one test case is therefore needed.

6.2.2 Statistical data coverage

All data can't use boundary value testing, e.g. a enumerated domain of colors:

```
Color : {Red, Green, Blue, Yellow, Black, White}
```

It is not possible to use boundary value testing here because there is no order of the values, they are not ranked. In these cases statistical data coverage method can be used instead.

6.2.2.1 Random-value coverage

This criterion requires that the values of a given data variable in the test suite follow a given statistical distribution, e.g. uniform, Poisson or Gaussian distribution.

6.3 Requirements-based criteria

Making sure that each requirement on the system is tested is a key issue in the testing process. The pass of all requirements ensures that the system delivers what it should. Therefore the requirements can be used both to help in the test generation and measure the level of coverage of the generated test cases.

There are two main approaches to achieve requirements coverage:

- Insert the requirements directly to the behavior model so that the test generation tool can ensure that they are fulfilled.
- Use some formal expression, like logic statements that drives the test generation tool to look for something special behavioral in the model.

6.4 Explicit test case specifications

Explicit test case specifications can be used to guide the test generation tool to examine some certain behavior of the system. These specifications can e.g. be a use case model which specifics some interesting path of the model that should be tested carefully.

The main advantage of these types of specifications is that they give extremely precise control over the generated test cases. The disadvantage is that it can be very time consuming creating these explicit test case specifications and you also lose some of the advantage with model-based testing which is letting the automatic test generation tool provide all test cases that are needed.

7 Conformiq Qtronic – Pilot modeling tool

In the pilot, where a part of the Base Station Controller (BSC) will be modeled, the modeling tool Qtronic Modeler and the automatic test generation tool Qtronic will be used. In this chapter these two tools will be shortly introduced, and the main features of them will be explained.

7.1 Conformiq

The Conformiq company was founded in 1998. Conformiq's headquarter is located in Finland. The company has 10 years of experience of Automated Test Design. The Conformiq Qtronic tool is their third evolution of their product.

The main tool that Conformiq provides is the Conformiq Qtronic, which is described by Conformiq in this way:

> Conformiq Qtronic is an ongoing attempt to provide an industrially applicable solution to the following technical problem: Create an automatic method that provided an object (a model) M that describes the external behavior of an open system (begin interpreted via well-defined semantics) constructs a strategy to test real-life black-box systems (implementations) I in order to find out if they have the same external behavior as M.

7.2 Qtronic Modeler

The Qtronic Modeler is a lightweight UML state chart editor that comes bundled with the main program Qtronic. This modeler makes it possible to easily create state machines that can be used in Qtronic directly without any need of converting to Qtronic Modeling Language (QML).

7.2.1 QML – Qtronic Modeling Language

The Qtronic Modeling Language is both a textural and a graphical notation. It is possible, even if it is not recommended, to design the whole model using just the textural notation. The textural notation is a superset of Java with some ideas from C#, plus some extra Qtronic specific features. The QML language does not include the standard libraries that come with Java or C#. This textural notation is sometimes called action language. The graphical notation uses UML state charts to create UML state machines.

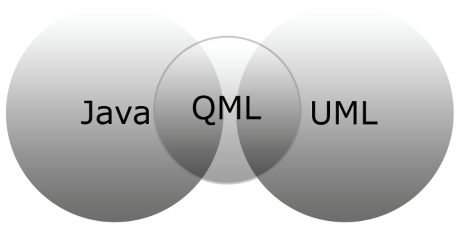


Figure 7.2.1 QML, Java and UML

7.2.1.1 Textural notation

The keywords in QML that do not exist in Java are listed below. QML has more differences compared to Java, but these differences have to do with different interpretation of the keywords. The ones listed below are the keywords that are new, regarding to what Java has.

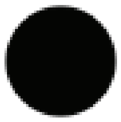
Keyword	*Meaning*
after	Defining that something will happen after some period of time.
checkpoint	Inserts a new checkpoint into the model, Qtronic will try and cover this.
Inbound	Defines an external inbound port to the system.
Outbound	Defines an external outbound port from the system.
omit	Specifies that the record field is omitted from the record instance.
record	Defines a record type, only records can communicate with an environment.
require	Require that the expression is true.
requirement	Inserts a requirement into the model.
system	Defines the system block which contains the external ports.

Table 7.2.1 Difference between Java and QML

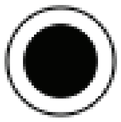
To get more information about differences between QML and Java read the Qtronic User Manual.

7.2.1.2 Graphical notation

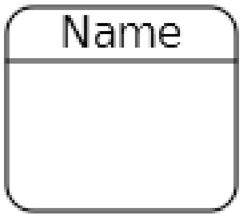
The graphical notation have some symbols that you build your UML state machines with, each of them will be briefly described below.



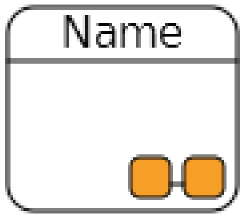
Initial State – Each state machine need to have one and only one starting point. This is where the execution starts.



Final State – This is a final state where the execution terminates. A model does not have to have a final state.



Basic State – This state is a normal state. The upper part contains the name of the state and the in the lower part some action language code can be places that will be executed when you are in this state. The lower part may be empty.

	**Sub State** – This state has a state machine inside itself. It is used for information hiding so that the model will be simpler to understand.
●	**Junction** – This state has similarities with the basic state but it has no unique name and can't contain any action language code.
→	**Transition** – This arc connects a source state with a destination state. Each transition can have a trigger, guard and/or action. All of them are optional. The syntax is `Trigger[Guard]/Action`. A trigger specifies the pattern of data to match and receive incoming data. The guard checks the incoming data and if the guard condition is true than the transition fires. If the transition fires than the Action will be performed.

7.2.2 Example

This state machine example models a file that contains a number of individuals. The individuals are used for setting up a network with cells, saying which cells that are neighbors with each other when configuring a Base Station Controller (BSC).

It is possible to increase the number of individuals and decrease the number of individuals.

- When increasing the number of individuals using command SAAII in the BSC, the BSC checks that it really is an increase and that the maximum limit is not exceeded.

- When decreasing the number of individuals using command (SAADI) in the BSC, the BSC checks that it is a decrease, the minimum limit is not reached and that no individual will be removed when the decrease is done.

The file can be illustrated like this:

Occ.	Occ.	Occ.	Occ.	Free	Occ.	Free
1	2	3	4	5	6	7

Highest used individual: 6 Number of individuals: 5

Figure 7.2.2 Free individuals example

The implementation makes it possible to have a free individual in between two occupied individuals, e.g. individual 5 is free.

The implementation had a fault that made the BSC to do a complete exchange failure, and a restart. When a BSC is forced to do a restart it is seen as something really bad, it almost never happens. The problem was that when the decrease command was used it compared with the number of used individual and not the highest used individual. They are the same when there are no free individuals in between, but when there are free individuals in between they are not the same anymore.

The problem was that the tester did not come up with a manual test case that tested what happened if you used the command SAADI, saying the new size should be five and there were some free individuals as in Figure 7.2.2.

The model that was produced using model-based testing looked like this:

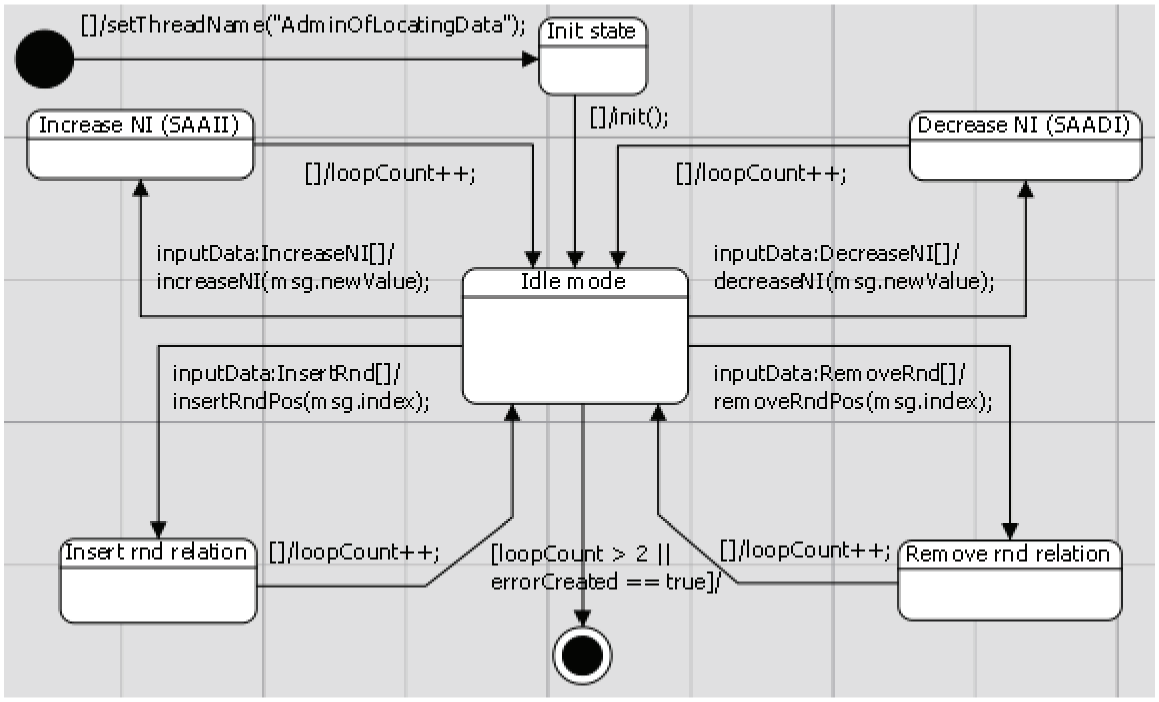


Figure 7.2.3 Free individuals state machine

It first initialized a vector with some occupied individuals in the beginning of the vector and let the rest of the individuals be free.

From the Idle mode state it had four options:

- Inserting a new relation to the vector, changed one of the free positions to occupied.
- Removing a relation from the vector, changed one of the occupied to free instead.
- Sending the command SAAII to the BSC, telling it to increase the number of allowed relations in the file. This made the checking as described above.

- Sending the command SAADI to the BSC, telling it to decrease the number of allowed relations in the file. It performed the required checking as described above.

Another interesting feature of this model is the `loopCount` variable. This loop variable forces Qtronic to do at least three operations before it can go to the final state. The test generation program (Qtronic) which is described in the next section has an option called "Only Finalized Runs". When this option is used it forces Qtronic to take each generated test case from the starting point of the model to a final state in the model. This is a good option and it should be used whenever it is possible. If the option is not used then Qtronic will have to decide for itself when it should end a test case, Qtronic can decide that it wants to end a test case after it has just taken the first transition. This will obviously not be an interesting test case, because this test case will not test anything interesting.

Qtronic was not able to find this fault using the general model that only said that it was not allowed to decrease below an occupied individual, what Qtronic generated was a test case that looked like the figure below.

Occ	Occ.	Occ.	Occ.	Free	Free	Free
1	2	3	4	5	6	7

Decrease to 1 individual

Occ
1

Error: Not allowed to decrease below occupied individual

Figure 7.2.4 Test case using general model

The model was changed so that it looked for one occupied individuals and then free individuals before. This is the test case that you really wanted Qtronic to produce. Now Qtronic were able to generate the correct test case, but now the model specifically asked for this test case. This is not the way you should do it when you design your behavioral model.

Occ.	Occ.	Occ.	Occ.	Free	Free	Occ.
1	2	3	4	5	6	7

Decrease to 5 individual

Occ.	Occ.	Occ.	Occ.	Free
1	2	3	4	5

Error: Not allowed to decrease below occupied individual

Figure 7.2.5 Test case generated using guide model

So the conclusion of this simple example is that it is hard for the test generation tool to find test cases that you did not expect.

7.3 Qtronic

When the SUT behavioral model has been produced it is time to automatically generate test cases. This is the purpose of the Conformiq Qtronic tool. The Qtronic tool takes the behavioral model as an input and automatically generates interesting test cases from the model.

The behavioral model describes how the system should work from the user's perspective. This model does not need to reflect the real structural model, which is the implementation. It is enough that it describes the intended behavior of the system.

Qtronic can be used in two different testing approaches. One is called online testing and the other is called offline test generation. In online testing Qtronic and the behavioral mode is directly connected with the system under test and in offline test generation Qtronic produces test cases that are saved so that they can be executed in the future.

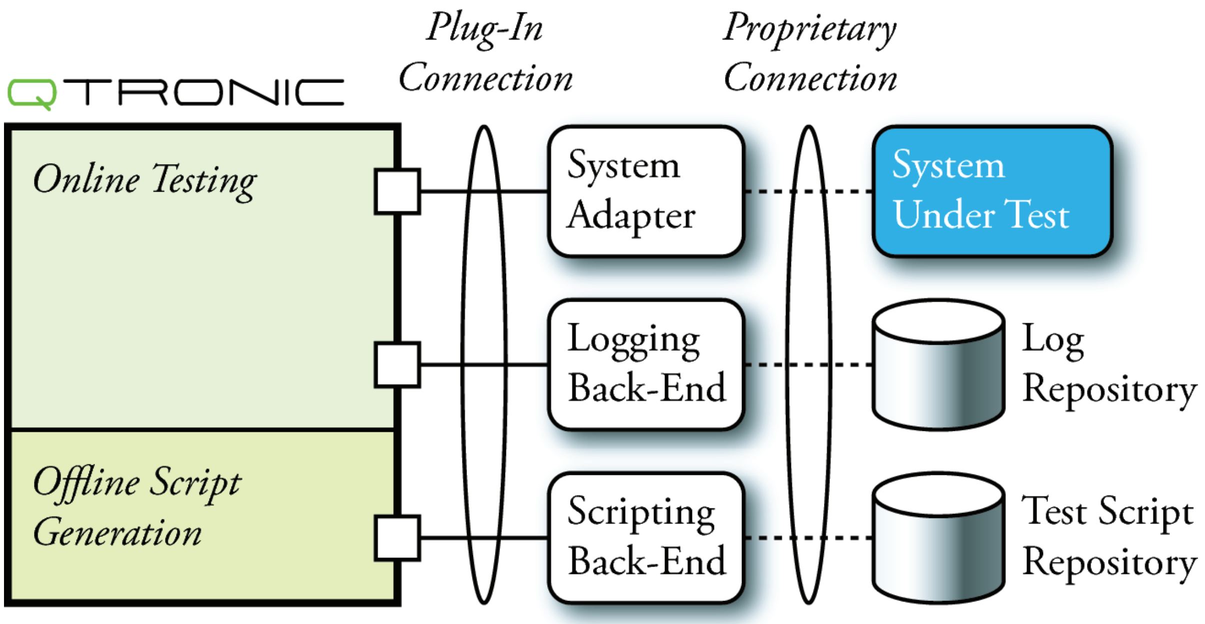


Figure 7.3.1 Qtronic overview

7.4 Online Testing

Using online testing Qtronic examines the behavioral model that is provided and it will select interesting test cases that are executed directly on the system under test. The system under test will report back to Qtronic what the response for the test case that is executed. Qtronic also runs the same test case on the behavioral model. These two test runs should produce the same result, otherwise there is some fault in the behavioral model or in the implementation. Qtronic will get online information about each test case and will then be able to change the next test case regarding to what information it has got.

To get the Qtronic and the system under test to understand each other an adapter is needed. This is because the behavioral model and the system under test have not entirely the same structure so some type of conversion will be needed.

The online testing procedure automates not only the test case generation phase but also the test execution phase.

7.5 Offline Test Generation

In offline testing Qtronic produces test cases by examine the behavioral model. The behavioral model is the only information that Qtronic has about the system under test.

In the offline mode Qtronic creates a library of test cases (assets). These test cases can later be executed on the SUT, either manually or in a more automatically fashion.

7.5.1 Script generation

Finding test cases is a difficult combinatorial task to do. Therefore Qtronic provide some options so that the user of Qtronic can select to a proper value to help Qtronic in the test generation phase.

To record the test cases that Qtronic is able to find a scripter generation adapter is used. Either this adapter is custom made for the system under test or some of the adapters that come bundled with Qtronic can be used.

The bundled adapters are able to produce test scripts in the following formats:

- HTML (Hyper Text Markup Language)
- TTCN-3 (Testing and Test Control Notation version 3)
- TCL (Tool Command Language)

The HTML adapter produces the most human readable test suite. In the report all coverage aspect of the model is shown, it tells how many percent of the model that Qtronic was able to cover, and shows which parts that it was unable to find a test case for.

It is possible to insert requirement statements into the behavioral model. The generated HTML report will build a matrix with all requirements and all test cases so that it will be easy to see which test case that fulfills which requirement.

The HTML report also shows exactly how each test case should be executed according to the behavioral model. Each test case can be viewed in a message sequence chart (MSC).

7.6 Model coverage methods

Qtronic provide a number of different coverage methods for analyzing the behavioral model and producing test cases. The tester/user will select which type of coverage Qtronic should try to achieve.

They are grouped into four categories that view the model from different directions.

- State charts
- Conditional branching
- Control flow
- All paths

7.6.1 State Charts (State Machine)

The state charts group has four different coverage methods. These coverage methods have to do with the graphical part of the behavioral model. The graphical part is the UML State Machine.

- State Coverage – All states in the UML State Machine must be visited at least one time in the generated test suite.
- Transition Coverage – All transitions in the UML State Machine must be taken at least one time in the generated test suite.
- 2-Transition Coverage – This coverage principle is the same as all-transition-pair that was described in the test case generation chapter. It is fulfilled if all transitions in to a state are tested together with all combinations of out transitions from a state.
- Implicit Consumption – This coverage method guides Qtronic to send signals that the model does not handle on any outgoing transition. With this feature selected Qtronic will send signals that the model does take care of and without this feature Qtronic will focus on what the model really is able to handle.

7.6.2 Conditional Branching

In the conditional branching group the focus is on generating test cases that examine how well different sides of branch can be covered.

- Boundary Value Analysis – This method groups an arithmetic condition into the minimum equivalence group and creates an input value for each equivalence group. If the condition is `x == y` then the equivalence groups will be `x < y`, `x == y`, `x > y`.
- Branch Coverage – Using this method all statements on the true and the false path of a branch will be covered. It ensures that an if-statement will be true in some test case and false in some other test case for example.

- Atomic Condition Coverage – Is the same as Condition Coverage that is explained in the test generation chapter. Qtronic will generate test inputs so that each condition in a decision will be tested with true and false.

7.6.3 Control Flow

This group is related to the general control flow in the behavioral model, it is the textural notation that is the main focus.

- Method Coverage – This coverage principle tells Qtronic to make sure that all methods in the textural notation are used at least once. It does not examine the method with different type of input parameters.

- Statement Coverage – Qtronic will be guided to cover all statements in the textural notation. A statement can for example be a variable assignment or a loop-statement.

7.6.4 All Paths Coverage

This coverage group tries to create test cases so that all paths in the model are covered.

- States – All possible paths to reach a state is created. This is done for all states in the UML state machine.

- Transitions – All possible combinations of transitions are taken. One test case for each of them will be produced.

- Control Flow – This coverage method respond to the conditional branches in the model and all combinations of conditional branches will be in the test suite.

7.7 Model checking

Before a test generation is started the model is checked for faults by Qtronic. It will examine that all signal types are declared, the right number of in and out ports are declared. Methods in the textural notation that is not in use will be omitted from the model so that they will not be in the coverage measurement.

The model checking reporting is user-friendly and tells were and why an error occurred.

When Qtronic is doing a test generation and finds a fault in the model it is reported as an assertion. Qtronic gives a trace stack showing how it reached this state. Qtronic looks for example for index out of bound when values are fetched from a vector or hash table, finding when a state machine reaches a deadlock state or when some other assertion is activated.

8 Pilot

This pilot will investigate how efficient the model-based testing methodology can be used in a normal flow of functional testing of a new feature in the base station controller.

First the GSM Network will be shortly introduced, followed by the manual testing procedure at the BSC department in Ericsson and then the actual feature will be described.

The feature that will be modeled has already been tested using the normal function testing procedure, which is manual testing. The manual test scope will be the baseline for the measuring of the model-based testing result. The pilot will produce test cases and these tests will be compared with the manual created tests.

8.1 GSM/GPRS Network

The Base Station System (BSS) is a node in the GSM/GPRS Network. The main components in the BSS are:

- Base Station Controller (BSC)
- Radio Base Station (RBS) / Base Transceiver Station (BTS)

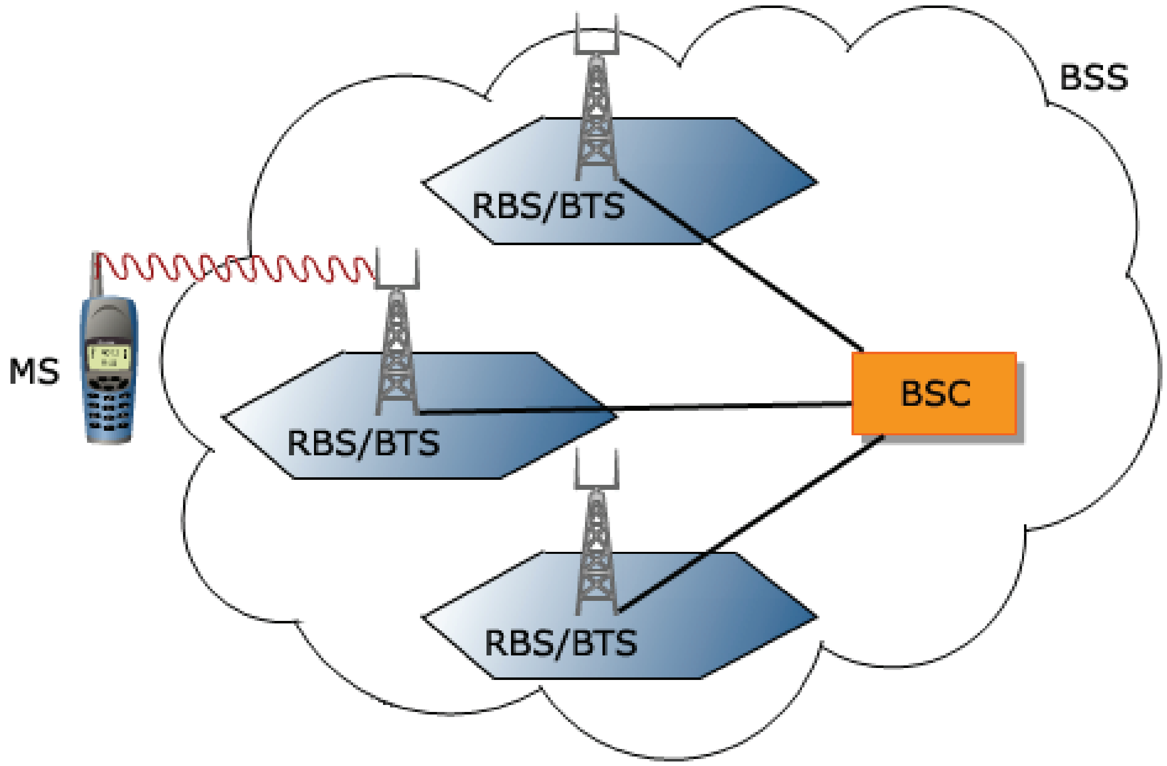


Figure 8.1.1 GSM/GPRS Network

The BSC handles most radio related functions. The BSC manages the radio network, e.g. configuration of the network and handling of connections to Mobile Stations (MS) including handovers. A handover can happen for example when a MS changes its position and come closer to another Radio Base Station (RBS), also called Base Transceiver Station (BTS). The RBS contains the antenna system, radio frequency power amplifiers, and digital signaling equipment.

8.2 Manual testing procedure

Before a new feature is implemented and tested a document called Implement Proposal (IP) is written. This document describes what should be implemented and what changes will be needed in each block of the BSC.

The designer updates the current code base and performs unit test on the block that he/she is working on. When the unit tests have passed, the updated code is given to a functional tester.

At the same time as the designer starts the update phase, the functional tester starts creating test cases. To his assistance the functional tester has several document, Implement Proposal, Requirement Specification (RS), Function Specification (FS), and Function Description (FD). The function specification describes a block in the BSC and the function description describes the block in more detail.

Before the functional tester starts executing the test cases there is an inspection meeting, where all test cases are examined and it is decided if the test coverage is enough. If the test coverage is sufficient then the functional tester starts the execution phase of the test cases.

When all test cases have been passed in function test the updated code is delivered to system test that will perform performance tests on the system.

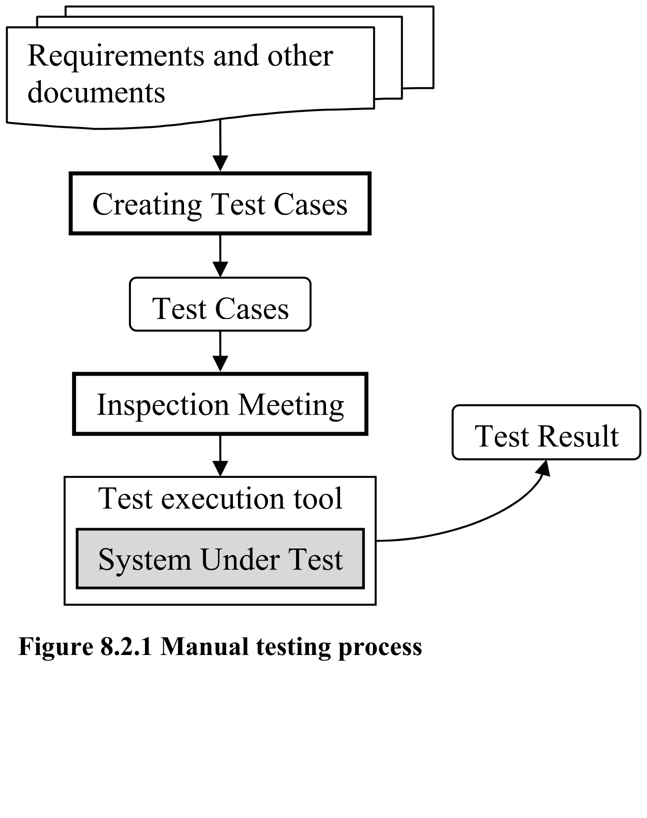


Figure 8.2.1 Manual testing process

8.3 *The modeled feature - RTTI*

This pilot will test a new feature in the BSC node.

The new feature that will be tested in the pilot is called Reduced Transmission Time Interval (RTTI). Before the introduction of this feature the only Transmission Time Interval (TTI) mode that existed was Basic Transmission Time Interval (BTTI).

The TTI mode decides how the data is sent over the channel from the network to the Mobile Station (MS). A mobile station is the device nearest the user, it can for example be a cellular phone, a computer or some other device that has a transmitter and a receiver (transceiver).

When a mobile station transmits or receives data, it is sent using one or more channels that are using a specific spectrum of the frequency domain.

8.3.1 Basic Transmission Time Interval (BTTI)

In the basic TTI mode a transmission of a data burst is done by that the mobile station and the base station controller first agrees on a channel to do the transmission on. The whole transmission is sent on this channel, from the beginning to the end.

Assuming that we have 8 channels that can be used for sending data simultaneously, the mobile station and the BSC agrees on sending on timeslot 3. The data will be sent on this channel until the time period ends. The figure below shows this, A, B, C and D is the data sent on this timeslot.

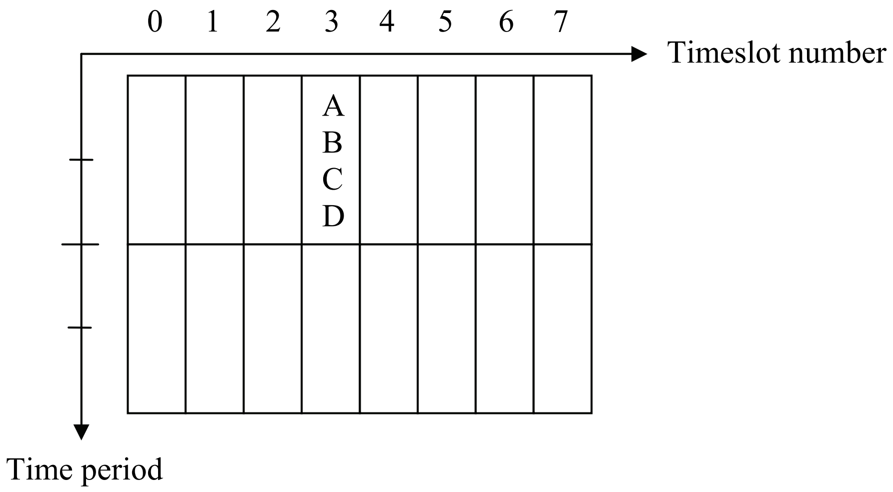


Figure 8.3.1 BTTI timeslot example

8.3.2 Reduced Transmission Time Interval (RTTI)

The reduced transmission time interval technique makes it possible to send the same data but using pairs of timeslots. The timeslots must be consecutive, meaning that having timeslot 3 and 4 is allowed for using RTTI but if the mobile stations have timeslots 3 and 5 than it is not possible to use RTTI.

The RTTI feature reduces the time that is needed for transferring the data over the air interface. The receiver will be able to quicker respond with its acknowledgement back to the transmitter. The data throughput is not increased using RTTI, it is only the Round Trip Time (RTT) that is lowered.

The mobile station can have a maximum of two RTTI pairs (four timeslots) in the downlink direction and one pair (two timeslots) in the uplink direction. This is the maximum but it depends on how many timeslots the mobile station can have simultaneously. If it can only have three timeslots in the downlink direction then it only can have one RTTI pair in the downlink direction, each pair needs two timeslots. If the mobile station can only have two timeslots in the downlink and two timeslot in the uplink but only three timeslots simultaneously then it can only have one RTTI pair in one of the directions.

Using the same figure that was introduced in the BTTI section, RTTI would look like this.

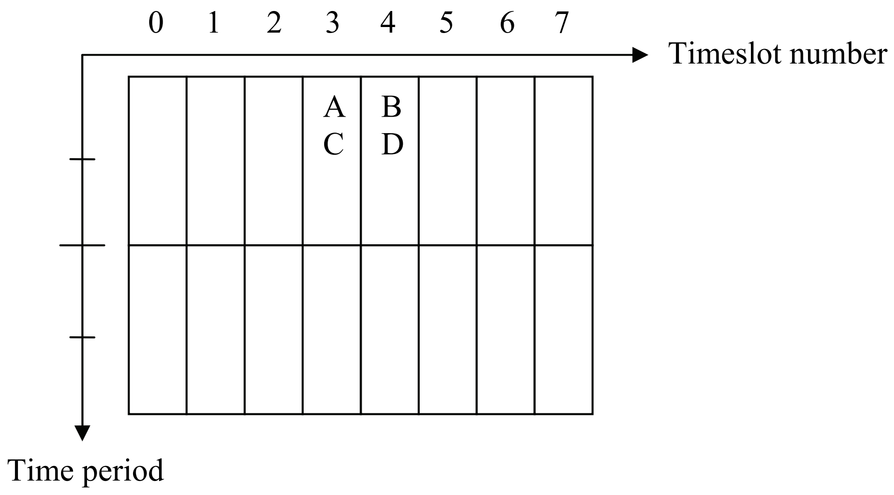


Figure 8.3.2 RTTI timeslot example

8.4 Model delimitations

This pilot has been limited to cover only the Connection Control block and the Channel Utilization block in the BSC and only the functions for reservation of a TBF (Temporary Block Flow) and what happens when the BSC detects that a channel is faulty. A TBF is something that groups the mobile station timeslots in one direction together. The mobile station can have one uplink TBF and one downlink TBF.

8.5 Model-Based Testing process delimitations

In this pilot the whole model-based testing process will not be investigated. This is because of the time budget and tight deadline for this pilot. In the picture below the process to the left is the general model-based testing process and to the right is the process that has been used in this pilot.

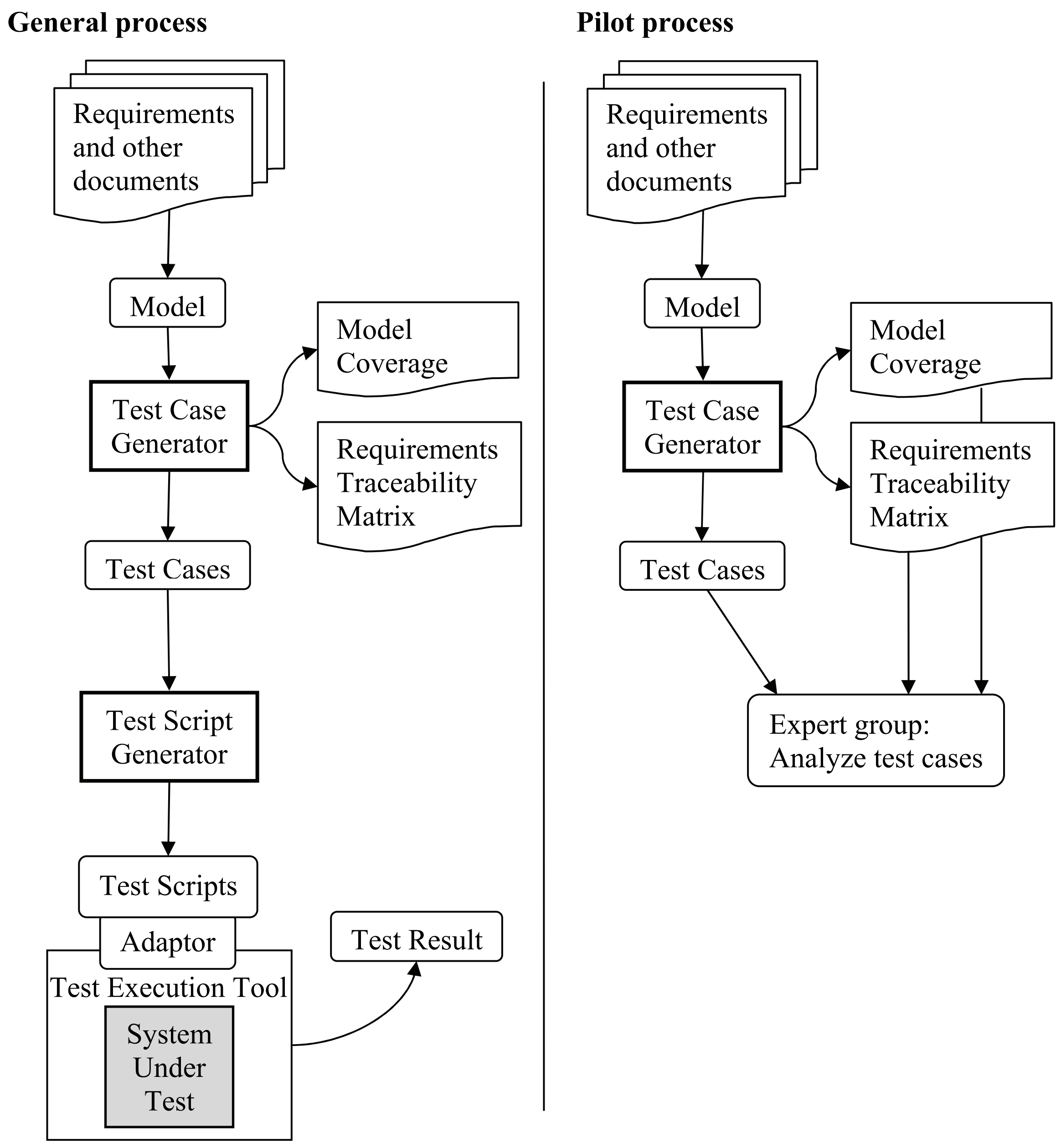


Figure 8.5.1 General MBT compared with the process used in the pilot

8.6 Input documents

The input documents used for this pilot has been the Implement Proposal (IP), Function Specification (FS) for the two modeled blocks and an introduction PowerPoint presentation of the RTTI feature.

The Ericsson Post-it - PDU GSM RAN Knowledge Database Wiki (Internal) has also been helpful when looking up acronyms and finding easy understood explanations of implementations in the BSC.

8.7 Modeling tool

The modeling tool used in this pilot has been the Conformiq Qtronic Modeler. It provides a lightweight framework for building models that can be directly used in Conformiq Qtronic without any transformations in format.

8.8 Test Case Generator

The test case generator for this pilot has been the Conformiq Qtronic tool. Several of different versions have been used during the pilot period. Starting with version 1.2.1 and then quickly moving to 1.3.0 (alpha) and in the end of the pilot using version 1.3.1. The stable version 1.3.1 has been used for generating the final test case results.

Qtronic can work in two different modes; Offline Script Generation and Online Testing. Online Testing means that Qtronic is directly connected to the system under test when generating test cases. In the Offline Script Generation mode Qtronic and the SUT are not connected together. The test cases are run on the system at a later stage. In this pilot only Offline Script Generation will be used.

Qtronic supports different adapters for saving the result of the test case generation step. The adapter used in this model will be the HTML Script Generator that comes bundled with Qtronic. This is because it provides the best visualizing of the generated test cases. The learning threshold is also the lowest for this adapter, which is good because the persons that will analyze the generated test result will rapidly need to understand how the test cases are described.

8.9 Analyze generated test cases

The generated test cases from Qtronic will be analyzed by a group of test experts.

The RTTI feature has already been tested using manual testing, which is the normal testing method at BSC function test. The manual test scope will be the baseline for the analysis of the test cases that Qtronic has generated.

The group members in the expert group are:

Name	Title	Department
Henrik Green	Senior Specialist R&D	BSC Design, FT & Env.
Håkan Persson	Function Tester	BSC Design, FT & Env.
Patrik Ekberg	BSC I&V Specialist	BSC I&V

Table 8.9.1 Names on the persons in the expert group

The persons in the expert group have not worked with the creation of the manual tests for the RTTI feature so their judgment when they will compare the manual test scope and the one generated by the model should not be influenced by that.

The BSC Integration & Verification department is the next step after the feature has passed function testing. The function testing department deliver their result to the I&V department.

The flow of the analysis will be:

1. The expert group will be introduced to model-based testing and the model will be explained so that all participants' understand the model. This will be done during a meeting.

2. Then the experts will have to do their own individual analysis of the test cases and get an opinion on each question. This step is to ensure that all experts have the time to decide what their own points are without being influenced by each other.

3. When all experts have decided how their points should be placed, they will have a meeting and discuss why they have placed their points as they have.

8.10 Measurements

The expert group will do their analysis using these measurement guidelines. The model-based testing result will be compared with the manual testing result.

- Test coverage of the TBF Reservation part
- Test coverage of the Faulty Channel part
- Consumed time
- Overview of the test scope
- Flexibility to adjust the test scope/coverage

Each bullet will be able to get 1, 2 or 3 points. Three is the highest and best value.

8.11 Model coverage setup

Qtronic will generate two different test scopes using two different coverage method setups. The expert group will examine the test cases from both setups. The category is indicating which part of the model the coverage method is working on. E.g. State Coverage ensures that all states in the UML state machine are visited.

8.11.1 Setup 1

Category	*Coverage method*
State Machine	State
State Machine	Transition
Control Flow	Method

Table 8.11.1 Pilot coverage setup 1

8.11.2 Setup 2

Category	*Coverage method*
State Machine	State
State Machine	Transition
Conditional Branching	Branch
Control Flow	Method

Table 8.11.2 Pilot coverage setup 2

9 Pilot model

The modeling tool used in the pilot model is the Qtronic Modeler. The model is built up by using three state machines. Each state machine is running on its on thread, and can change state independently of each other. All three state machines are connected together and can communicate through signals with each other.

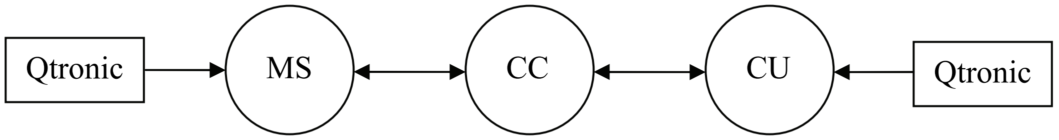


Figure 9.1 Overview of the pilot model

Qtronic has the possibility to generate signals to the Mobile Stations (MS) and the Channel Utilization (CU) state machines. All message passing between state machines are signals, and a signal must be of the type record. This is a requirement from Qtronic itself.

9.1 Mobile Stations (MS) State Machine

The Mobile Stations state machine handles the mobile stations (e.g. a mobil phone) in the network, and performs TBF requests.

A TBF is a structure that groups a mobile station's timeslots together. The TBF is directed, it can either be an uplink TBF or a downlink TBF. An uplink is for sending data from the mobile station to the network and a downlink is for receiving data from the network.

First the Mobile Stations state machine configures what capabilities the mobile stations in the network should have. It is up to Qtronic to decide what capabilities the mobile station should have in each test case.

The available capabilities are:

- RTTI – Indicates that the mobile station can use RTTI
- FANR – Indicates that the mobile station can use FANR (Fast Ack/Nack Reporting)
- Multi slot class – The multi slot class says how many uplink timeslot and downlink timeslots a mobile station can have at a maximum.

When the Mobile Stations state machine has configured all mobile stations in the network it will go into a new mode. In this mode Qtronic will be able to send a TBF Request for a mobile station. This is done by sending the `TBFSetup` signal to the Connection Control.

The Mobile Station state machine will wait until it receives a positive or negative `ReservationResponse` from the Connection Control.

9.1.1 Signals

Record name	*From*	*To*	*Description*
SaveConfiguration	Qtronic	MS	Save a mobile station configuration
MSSetup	MS	CC	All mobile stations are created
RequestTBF	Qtronic	MS	Request a TBF setup
TBFSetup	MS	CC	Set up a TBF
ReservationResponse	CC	MS	TBF response on the request
FaultyChannelDummy	Qtronic	MS	Make one channel faulty
MSFaultyChannelDummy	MS	CU	Tell CU to make a channel faulty
IncreaseOperationCount	CC	MS	Make MS increase the operation counter
OutMsg	MS	Qtronic	Send a text String

Table 9.1.1 Input and output signals in MS

9.2 Connection Control (CC) State Machine

The Connection Control state machine is the bridge between the mobile stations in the network and the Channel Utilization that has the knowledge about the channel. Connection Control performs some checking on the requested TBF setup and then either sends the channel request to Channel Utilization or reports an error to the Mobile Stations state machine.

When CC gets the `TBFSetup` signal from the MS it starts analyzing the request. This signal informs CC which type of TBF the mobile station wants to setup, if it is an uplink or downlink TBF and if the channel type will be Common Control CHannel (CCCH) or Packet Associated Control CHannel (PACCH). First the mobile station must set up a CCCH channel and then it is allowed to request a PACCH.

The CC state machine assumes that the mobile station does not always make the right TBF request so CC will do some checking to control that the TBF setup request is valid. Connection Control will check these criteria:

- The mobile station can only have one TBF in each direction, therefore the CC will check that the mobile station does not have a TBF in the same direction as the new TBF request has.

- If the TBF request is of channel type PACCH, then it is required that the mobile station already has a TBF in the opposite direction and that this TBF is of CCCH type.

If these requirements are fulfilled then Connection Control will send the `TBFReservation` signal to the Channel Utilization state machine saying that it should try and do the best possible reservation. If CC finds that all requirements on the TBF setup are not fulfilled then it will report it as an `Error` and inform the Mobile Station state machine that the request was not possible.

9.2.1 Signals

Record name	From	To	Description
MSSetup	MS	CC	All mobile stations are created
CCSetup	CC	CU	Connection Control is up and running
TBFSetup	MS	CC	Set up a TBF
TBFReservation	CC	CU	The TBF request
ReservationMade	CU	CC	Best possible reservation
ReservationResponse	CC	MS	TBF response on the request
FaultyChannel	CU	CC	The removed channels
IncreaseOperationCount	CC	MS	Make MS increase the operation counter
OutMsg	CC	Qtronic	Send a text String
Error	CC	Qtronic	Send a error String

Table 9.2.1 Input and output signals in CC

9.3 *Channel Utilization (CU) State Machine*

It is the Channel Utilization where most of the calculation is made. The Channel Utilization state machine manages the frame. The frame is used for holding and controlling the timeslots, where the actual data is sent over the air interface.

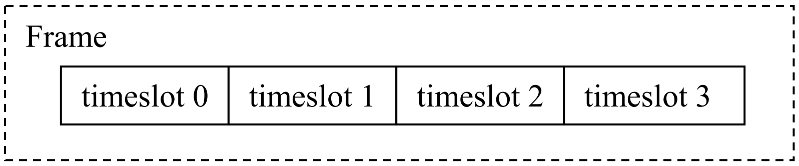


Figure 9.3.1 Timeslot frame in CU

The frame can be of size four to eight, meaning that it can hold four to eight timeslots. Each timeslot can be of type E-PDCH (Packet Data CHannel) or R-PDCH. To be able to use RTTI, there must be at least two consecutive R-PDCHs in the frame.

Channel Utilization calculates the best possible reservation according to what capabilities the mobile station has and how the frame is occupied and which type of PDCH it has.

During the initializing phase of the Channel Utilization state machine Qtronic will decide how big the frame should be and which type of PDCH it should contain and where they should be placed in the frame.

When Qtronic have decided about what the frame should look like, the Channel Utilization state machine will be in the idle mode waiting on:

- A signal telling Channel Utilization that the Dynamic TTI mode has changed.
- A TBF reservation request from Connection Control.
- A signal telling Channel Utilization that it should make a channel faulty.

9.3.1 Dynamic TTI mode

The dynamic transmission time interval mode tells Channel Utilization what type of traffic that has the highest priority for the moment. Dynamic TTI has three different states:

- Neutral State – Channel Utilization is allowed to sacrifice one uplink and/or downlink channel according to the multi slot class.
- DLBiased – Channel Utilization is not allowed to sacrifice any downlink channels when doing a TBF reservation according to the multi slot class. This is because the downlink direction is prioritized.
- ULBiased – Channel Utilization is not allowed to sacrifice any uplink channels when doing a TBF reservation according to the multi slot class. This is because the uplink direction is prioritized.

The multi slot class is telling how many timeslots a mobile can have at a maximum. E.g. a mobile station that is in multi slot class 3 can have 2 timeslot in the downlink direction and 2 timeslots in the uplink direction, but only 3 timeslots in total. The multi slot class table is in the appendix named Multi slot class table.

9.3.2 TBF reservation

When the signal `TBFReservation` comes from Connection Control it has information about the mobile station's capabilities and which type of TBF that it wants to setup.

Channel Utilization knows what the frame with the timeslots looks like, which timeslots that are occupied and of what type the timeslots are. Channel Utilization will give the best possible reservation back to Connection Control though the signal `ReservationMade`.

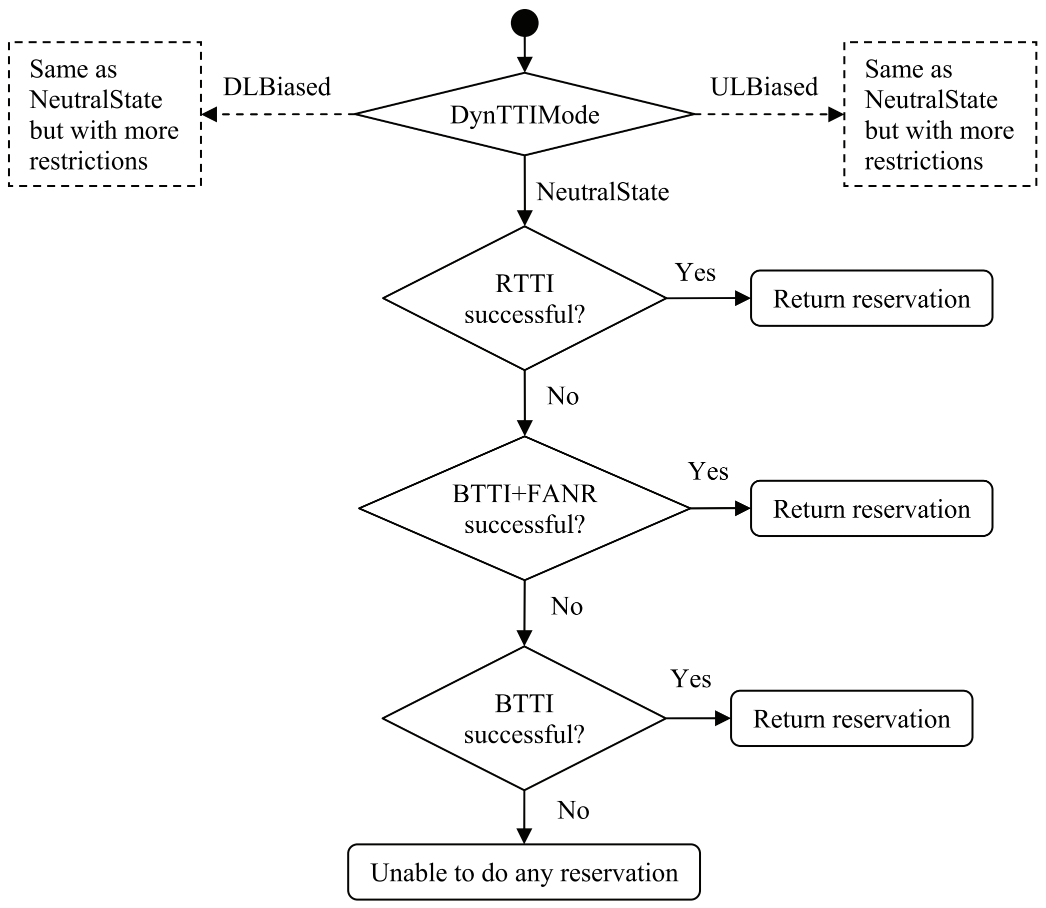


Figure 9.3.2 TBF reservation algorithm in CU

The reservation algorithm first checks which dynamic TTI mode the channel is in. If the mobile station has RTTI capability it first tries to do a RTTI reservation. To be able to do a RTTI reservation it needs at least two free R-PDCH timeslots that are located together in the frame.

RTTI examples:

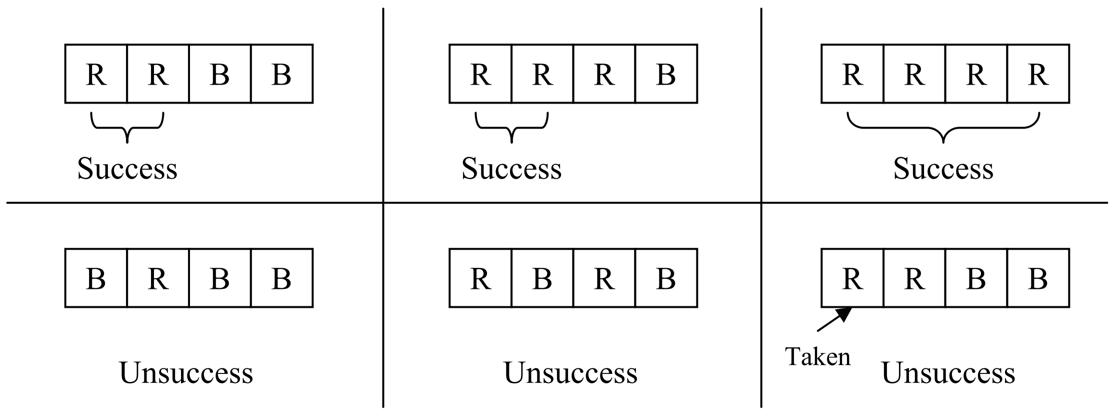


Figure 9.3.3 RTTI allocation examples

If the mobile does not support RTTI or it is impossible to do a RTTI reservation, then Channel Utilization will try doing a BTTI reservation instead. If the mobile station has FANR capability then it will do a BTTI+FANR otherwise only a BTTI.

The BTTI reservation is not working in pairs, and the timeslots does not need to be situated together, even do it is desired. A BTTI reservation does not acquire a R-PDCH to work, so it is more flexible.

BTTI examples:

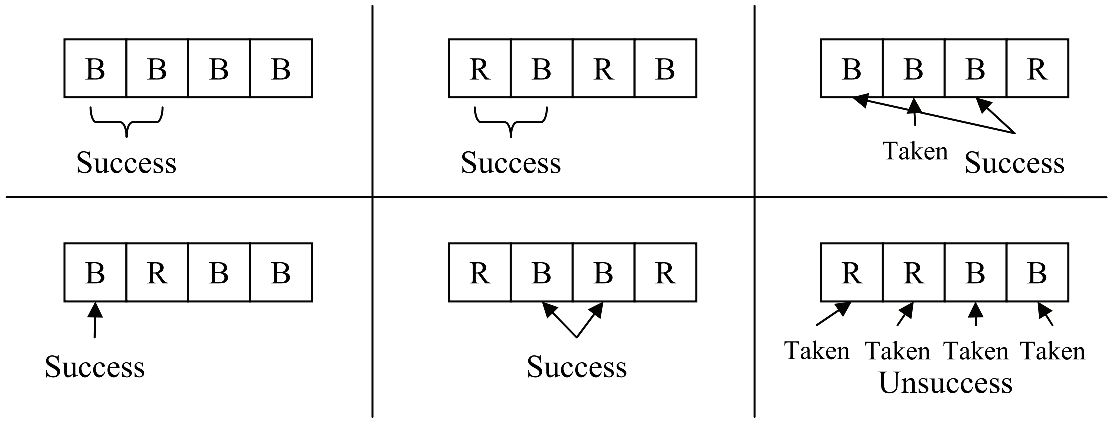


Figure 9.3.4 BTTI allocation examples

If Channel Utilization was unable to do a BTTI reservation request, e.g. all timeslots were occupied. Then it will report back to Connection Control that it was impossible to do any channel reservation, on the specific request.

9.3.3 Faulty Channel

When the signal `MakeChannelFaulty` is signaled from Qtronic it will carry an identifier saying which channel/timeslot in the frame that should be made faulty.

Channel Utilization will perform the actual make channel faulty task. It examines the faulty channel. If a mobile station is using this channel, the Channel Utilization will decide if more channels for this mobile need to be removed. Channel Utilization will do this judgment using the information about which TTI mode the mobile is in, if the faulty channel was essential to the mobile. When using RTTI the first pair will be essential, and when using BTTI the first timeslot will be essential the rest will be non-essential.

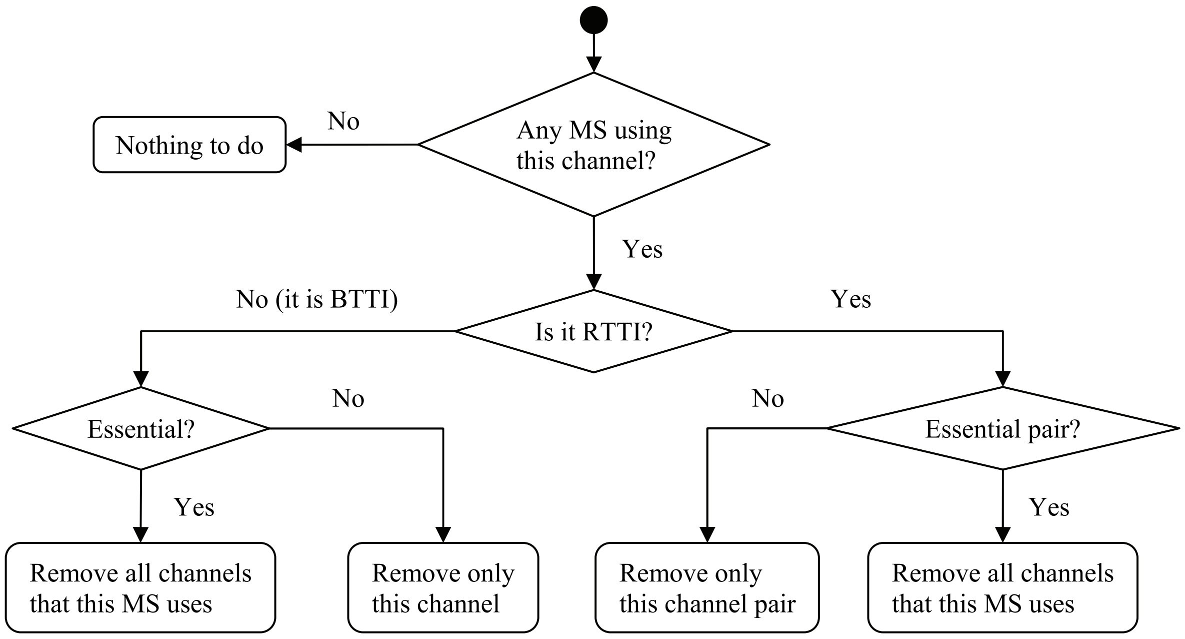

Nothing to do
No
Any MS using this channel?
Yes
No (it is BTTI)
Is it RTTI?
Yes
Essential?
No
No
Essential pair?
Yes
Yes
Remove all channels that this MS uses
Remove only this channel
Remove only this channel pair
Remove all channels that this MS uses

Figure 9.3.5 Faulty Channel algorithm in CU

The faulty channel and the other channels that were removed due to the faulty channel are reported to Connection Control through the signal `FaultyChannel`.

9.3.4 Signals

Record name	From	To	Description
CCSetup	CC	CU	Connection Control is up and running
FrameSize	Qtronic	CU	Decide how many timeslots needed
ForceRChannels	Qtronic	CU	Force a number of them to be R-PDCH
TimeSlotType	Qtronic	CU	Decide channel type
DynTTIConfig	Qtronic	CU	Decide dynamic TTI mode
TBFReservation	CC	CU	The TBF request
ReservationMade	CU	CC	Best possible reservation
MSFaultyChannelDummy	MS	CU	Tell CU to make a channel faulty
MakeChannelFaulty	Qtronic	CU	Make a specific channel faulty
FaultyChannel	CU	CC	The removed channels

Table 9.3.1 Input and output signals in CU

9.4 TBF reservation signaling

1. When doing a TBF reservation it all starts with Qtronic signaling `RequestTBF` to Mobile Stations state machine.

2. The Mobile Stations will send `TBFSetup` to Connection Control. The signal will carry information about which type of TBF the mobile station wants.

3. Connection Control will examine the TBF request and forward it to Channel Utilization and if everything is fine, use the signal `TBFReservation`. Otherwise an error is sent to the Mobile Stations state machine using signals `Error` and `ReservationResponse`.

4. Channel Utilization will calculate the best possible reservation and return this reservation to Connection Control using signal `ReservationMade`.

5. Connection Control will forward the reservation back to the Mobile Stations state machine in the signal `ReservationResponse`.

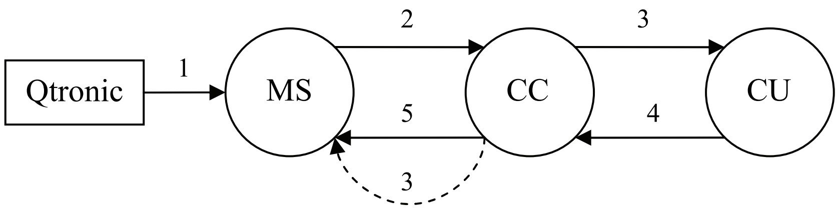


Figure 9.4.1 Signaling when a TBF is reserved

9.5 Faulty Channel signaling

0. Qtronic will send the signal `FaultyChannelDummy` to the Mobile Stations state machine and MS will immediately send `MSFaultyChannelDummy` to Channel Utilization. This is for preventing possible deadlocks in the state machines. This is more discussed in section 11.1.6.

1. Qtronic will generate the signal `MakeChannelFaulty` which indicates which channel that has become faulty.

2. Channel Utilization will perform so checking and decide if any other channels need to be removed due to the faulty channel. The signal `FaultyChannel` will contain this information, and it is then sent to Connection Control.

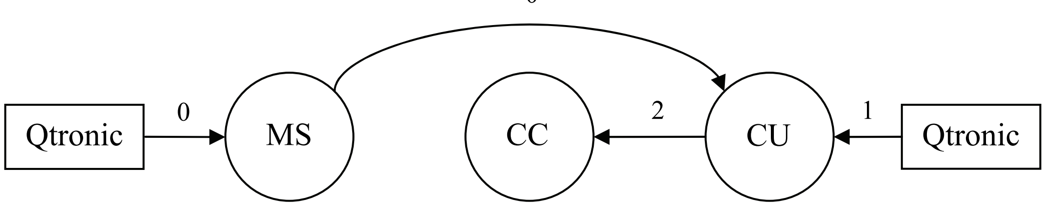


Figure 9.5.1 Signaling when a channel becomes faulty

10 Pilot results

In this chapter the measured result from the pilot will be presented. The result comes from what the analysis from the expert group has come up with.

First the points from the analysis will be presented and then a summary of the thoughts from the meeting with the experts will be presented.

10.1 The experts' points

These tables show how the experts' placed there points. The first table presents the points that the model-based testing approach got and the second table shows the points for the manual testing approach. The maximum points any of the categories can get are three points. Totally one of the approaches can get 45 points if each expert gives the maximum point on each measurement.

10.1.1 Model-Based Testing

Measured	*Henrik*	*Håkan*	*Patrik*
Test coverage of TBF reservation part	3	2	3
Test coverage of Faulty Channel part	2	2	2
Consumed time	1	1	1
Overview of the test scope	2	2	1
Flexibility to adjust the test scope/coverage	3	3	2
Summary	**11**	**10**	**9**

Table 10.1.1 Points given by the experts on the Model-Based Testing

The model-based testing got a total score of 30 points out of a maximum 45 points. Two of the experts gave this approach two third or more of the total points which can be seen as quite good. The experts had mainly the same opinion regarding the model-based result.

10.1.2 Manual Testing

Measured	*Henrik*	*Håkan*	*Patrik*
Test coverage of TBF reservation part	2	1	2
Test coverage of Faulty Channel part	2	2	2
Consumed time	2	2	2
Overview of the test scope	1	2	3
Flexibility to adjust the test scope/coverage	1	1	1
Summary	**8**	**8**	**10**

Table 10.1.2 Points given by the experts on the Manual Testing

The manual testing approach scored 26 point which is 4 points less than the model-based approach obtained. The model-based testing received roughly 9 % better result compared with the manual testing.

10.2 Test coverage of TBF Reservation part

The model covers interesting parts of the RTTI, but unfortunately it has some limitations regarding the functionality. The manual test scope covers a larger part of the RTTI feature. If you only examine the parts that the model covers then the model has a greater number of interesting test cases.

The model tests more combinations of mobile stations with different settings. Settings used are different multi slot classes, RTTI, FANR and BTTI. The test cases generated from the model test more what happens when the different type of traffic is prioritized.

Even though the model has its limitations it finds more interesting things than the manual test scope.

It is hard to see the test coverage of the model. The generated test report gives which parts that are covered and how many percent of the model that is covered but it is hard to see which part each test case is covering. The model and the test cases should be glued more together. It would be good if the tool could provide a graphical overview of each test case so that you could trace them in the model. It would increase the understanding of the test cases.

Some of the test cases in the manual testing are not really relevant and some things have been missed. Everyone is terrified to remove a test case when the inspection meeting is held. It is hard to find all variants that are needed to be tested, and here the model can help.

A problem with manual testing is that it is easily the case that the whole test scope is a bit of the track, that the created test cases do not test all interesting parts that need to be tested. It is very hard to realize that the scope is testing the wrong things and with the help of the model it will be easier to realize in an early stage that something is wrong. This is because the model should be produced in an early stage together with the designers, so that both parts can agree on the model. The model will be the thing that units the design team and the functional testing team.

10.3 Test coverage of Faulty Channel part

The generated test cases from the model were quite few and many of them looked strange. It seemed that some of them were not ended in the correct way and sometimes they were ended before anything interesting had happened.

An example:

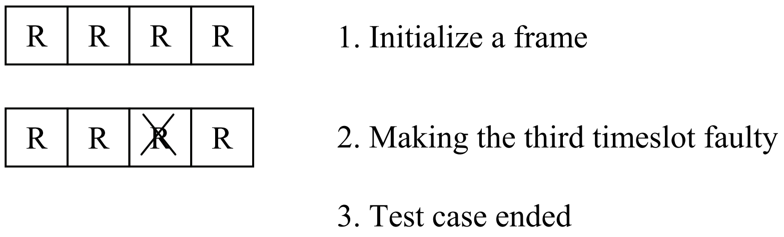


Figure 10.3.1 Example of a test case that ended too quickly

It feels as if the generated test cases in this part of the model are not so good. The TBF reservation part had more combinations of different inputs.

In general for the manual test scope there are parts that have been missed and when the model is correct then you see that more variants of inputs are covered. The next step would be to decide which variants that is really interesting to perform.

10.4 Consumed time

During the pilot the time has been recorded that was needed to build the model and generate the test cases. The result is in this section.

10.4.1 Manual Testing

The measurement of time has not been done in a precise way during the manual testing. The manual testing took place before this master thesis and the normal situation at BSC Design is that they don't measure the time in an exact manner.

The testers that worked with the RTTI feature have estimated the time that they used to about 100 hours. This time has been checked with the time plan for the RTTI feature and it seems to be correct.

During these 100 hours the whole feature was tested, which was not the case using the model-based testing approach.

10.4.2 Model-Based Testing

The pilot took around 190 hours in total to produce. Each slice in the figure below indicates how much time that was spent on each task in the pilot. But it is really hard to draw boundaries between all tasks in the pilot.

It was the first time this tool was used and some time was needed to learn it. Because there were no old models to reuse then everything had to be built from scratch. To be able to test the RTTI feature more things around the feature was needed to be created. It was necessary to decide how a timeslot should be modeled etc.

After the generated test cases have been produced, there are a lot of things that need to be done manually, e.g. writing test specifications, which describes an overview of the test case and naming the different test cases. The tool used in this pilot did not provide any help for this. This is of course only needed if the whole model-based process is not implemented. For this process it might be necessary to save the model instead as it is done now saving the test cases. The problem will arise when the model is saved and then something must be added to the model. Will it be possible to separate the newly created test cases from the old ones?

We are convinced that the model-based testing approach will need more time then the manual testing, but hopefully the testing result will be better so that it is worth the extra time.

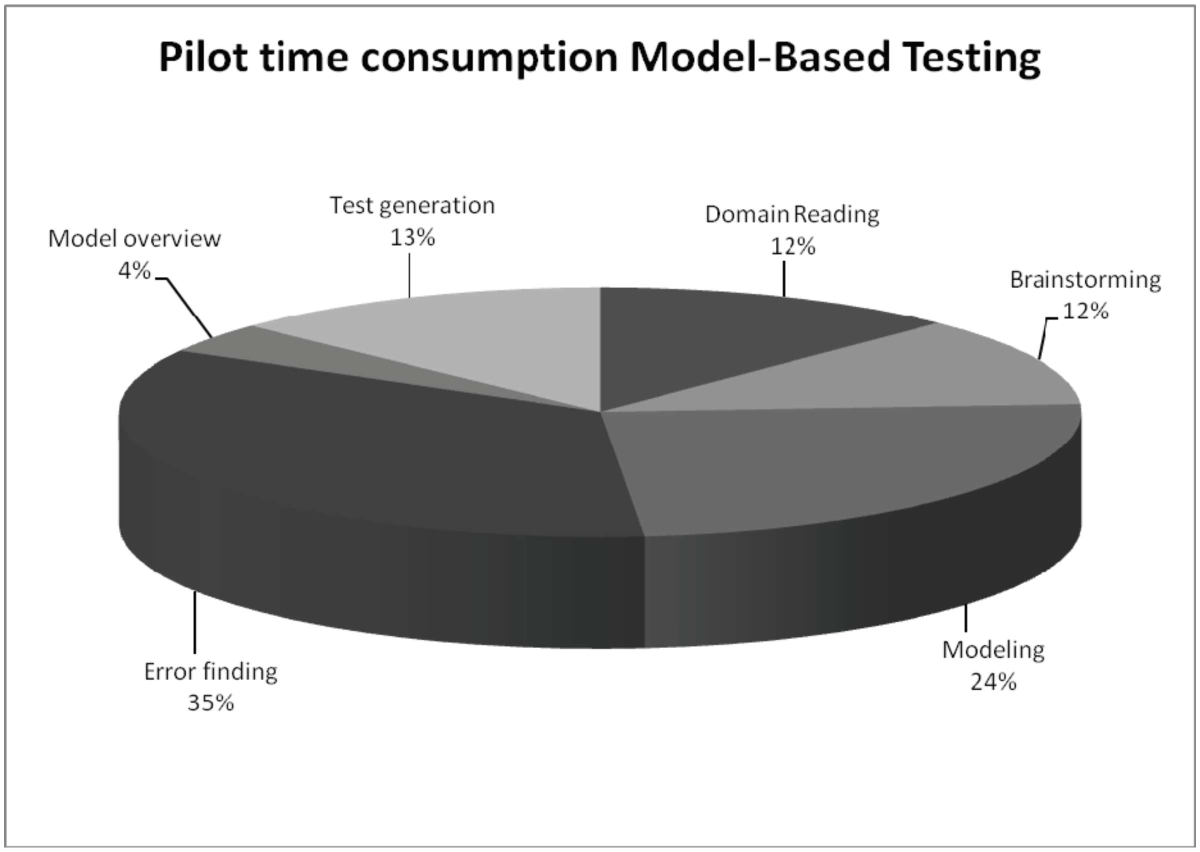


Figure 10.4.1 Consumed time in the pilot

The domain reading slice was pure reading and understanding of the RTTI feature and the BSC. It also contained reading of the Implement Proposal (IP), talking with people that had expert knowledge and reading the functional descriptions of the Connection Control and Channel Utilization.

The brainstorming period was when the functionality was partitioned into different subsystems. In this period it was also decided which functionality were needed for testing the RTTI feature.

The pilot model was designed during the modeling period. All code and state machines were produced here.

There is not really a distinct line between error finding and modeling, but the error finding part was when the model integration took place. To be able to find an error in the model, or in Qtronic, Qtronic had to generate test cases from the model and then the result had to be examined. A lot of time was used just to make Qtronic cover the whole model, change the model and generate again. Each test generation took from 1 to 20 hours. This is the main reason why the error finding period was so time consuming.

The model overview was a short period when the requirements were examined to ensure that the model fulfilled them.

The final phase was test generation and here different type of settings were used to generate test cases. The option Only Finalized Runs were used but it was never successful. This was because all state machines needed to have a final state. The instruction in the Qtronic manual was incorrect. It said “Each test case must take the system into a final state”, more correctly it should be “Each thread must be taken to a final state”.

10.5 Overview of the test scope

It is really hard to give correct points on the overview of the test scope. If you only look at the generated test cases for the model-based approach then it would only get one point because it is really hard to understand the test cases without the model. If you know exactly how the model is working and use it together with the generated test cases then it would be three points. But the tool is missing an easy way to examine each test case together with the model. It would be good if you could follow each test case in the model in an easy way.

If model-based testing should be used then we believe that the model should be a collaboration between the design team and the test team. The model should be produced in as early phase as possible. This is because the model must be correct and everyone must understand the model and which parts that the test focus will be in. This will require a new work flow for both design and test, and you gain a tighter collaboration between the two teams.

The overview using the model is one of the best features with the model-based approach. Function test will probably be able to reduce the needed time, because design and test will agree on the model. It will be possible to find errors e.g. in the Implement Proposal (IP) in an early phase and therefore reduce the time and needed resources. If the decision will be that function test will build the model on their own with no help from the design then the model will be a new source of error, because if the model is faulty then it will produce test cases that will not work.

The opinion regarding overview of the manual test scope was not united. Some of the experts think that is hard to understand were each test case comes from if you look at the Implement Proposal (IP). Other experts think that it is easy to see the overview of the manual test scope.

10.6 Flexibility to adjust the test scope/coverage

If the model construction phase takes place at the same time as the design phase then it will be very flexible. It will be possible to try out and modify the model in an early phase, change details and decide which type of coverage methods to use when generating test cases.

The strength with the model-based testing approach is that it will be possible to generate more test cases easily by adding some more test coverage method, e.g. branch coverage in test setup 2 gave 10 extra test cases.

All experts did not think that the model-based testing should get the highest value in this category. This was because some manual work is needed after the test generation phase, e.g. name the different test cases. If the Implement Proposal has some fault and need to be changed after the model has been created a lot of changes need to take place in the model. Once the model change has been done then it will be easy to generate new test cases and all of them will be up to date. When the IP changes and the manual testing process is used then it is hard do know which test cases that need to be changed and which new test cases are needed. The model will help in this process but it some extra time in updating the model must be used.

11 Lessons learned when modeling

In this chapter the things learned from the pilot will be presented. The guidelines are supposed to be a helping hand for persons that are new to model-based testing and the Qtronic tool. The two last sections describe which faults/bugs that was discovered in the Qtronic tool during the pilot and what improvements would make Qtronic an even better tool.

11.1 Guidelines

The guidelines that will be presented in this section are valuable when you design your first model using Qtronic. If you follow these guidelines then hopefully your generated test cases will be better and the required time for building the model will be less.

Some of the guidelines are solutions to problems that came up during the pilot.

11.1.1 Qtronic Random function

When building the Mobile Stations state machine, and specifically the part of the state machine that generates the different type of mobile stations that will be needed in each test case some type of randomness was needed. This was because the mobile station could have different capabilities, e.g. RTTI, FANR and multi slot class, and for each test case Qtronic needed to generate a mobile station that had the right capabilities.

The obvious thought was *Randomness == The built in Qtronic Random function*. This was a mistake. The Qtronic Random function does not produce a random result in some sense. Instead that the model is examined by Qtronic, and if the “random” value and if the behavior in the model depends on this “random” value then Qtronic will generate interesting values to make the selected coverage criteria fulfilled.

An example:

```
if (random(15) < 10)
   statement1();
else
   statement2();
```

If the above code is used in a state in the model and branch coverage is selected as the coverage method. Then Qtronic will generate “random” so that both the true and the false path of the if-statement will be executed.

But if the coverage method is statement coverage then Qtronic will only generate a “random” value so that the true side of the if-statement is executed. Then it is not really random.

When using the random function you are telling Qtronic that the system that you are modeling has some random feature. If this is correct then the random function is the right choice, but if the random function is used for generating e.g. random input parameters then you are doing it in a wrong way. Kimmo Nupponen, Lead Developer at Conformiq wrote in an e-mail conversation “A word of warning: When running Qtronic in offline script generation, then it is most often a misconception to have *random* in the model as this is a source of non-determinism and models in script generation must be deterministic”.

The solution is to let all of this “randomness” to be taken care of Qtronic. Qtronic generates the needed input signals so that the selected coverage methods are fulfilled.

11.1.2 Use require on signals

Qtronic communicates with the model using signals. These signals must be of the type `record`. A record is a structure that can hold other type, e.g. Boolean, integer, Strings and records.

```
record myRecord
{
   int myInt;
   boolean myBool;
   String myStr;
}
```

Boolean variables can only be true or false so they have a restricted domain, but integers, String and other data types have a much larger domain space, almost infinite. If the allowed domain space is not regulated then Qtronic will not be able to do a good job. Qtronic must analyze the model and select input values that are interesting for the model and if the range of the integer is not decreased the Qtronic will have a lot of values to test.

The way of saying to Qtronic which values it should test is using the `require` statement or using the signal guard. A transition statement can look like this for example:

```
mySignal:myRecord[msg.myInt >= 0 && msg.myInt < 10]/myFunction(msg.myInt);
```

The guard in inside the `[ ]` brackets, `msg` is a special Qtronic variable that is used when you want to address the records variables. Now Qtronic will only generate signals with `myInt` in the interval [0, 9].

The `require` statement works in a similar way:

```
private void myFunction(int value)
{
   require value >= 5;
}
```

If this method is called when the transition is taken then `myInt` will be in the interval [5, 9].

The require statement or the signal guard for decreasing the range of variables should always be used, because it will decrease the time that Qtronic will need for doing the model analyze.

11.1.3 Use Only Finalized Runs when possible

In the Conformiq Qtronic tool, which is used for automatic test generation, there is an option called “Only Finalized Runs”. This feature forces Qtronic always to take a test case to a final state. If this option is not used then Qtronic can decide to stop a test case directly after it has begun, and this will obviously not be an interesting test case.

To be able to use this option all the state machines must have a final state. When using a final state it is recommendable to use a counter that counts how many operations that have been used. When doing so the guard to the final state can be controlled.

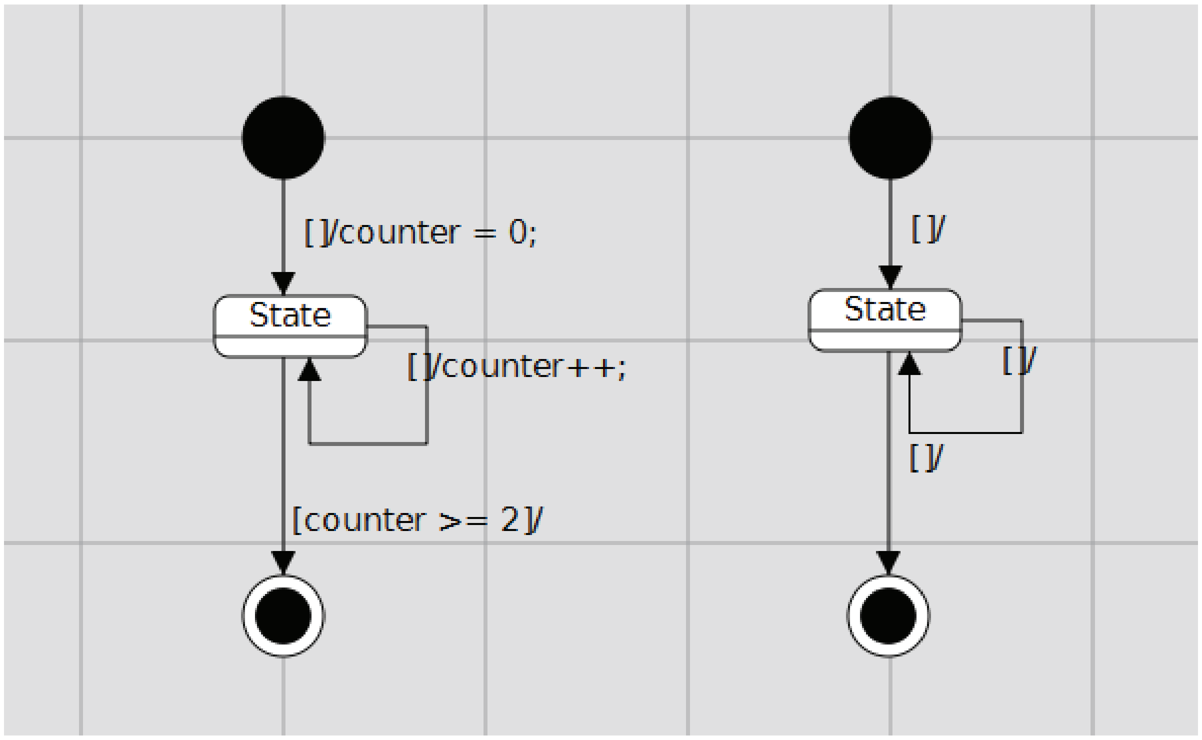


Figure 11.1.1 Only Finalized Runs example

The state machine to the right does not use the counter variable, here Qtronic can decide to go to the final state directly when it is in the state called “State”. In the left state machine the counter variable method is used. Qtronic will now need to take the self-loop at least two times before it can go to the final state and end the test case. By using the counter variable you can control the test cases that Qtronic will produce satisfactory. Qtronic will be forced to perform some action in the model.

In the Qtronic user manual the following is found about Only Finalized Runs, “only such test cases are generated that take the *system* to a state that is considered to be *final*”. After the pilot was ended Conformiq released a new document saying this about instead “only such test cases are accepted to the generated test suite that would cause all *threads* in the model to *terminate*”. It is a big difference between system and thread here. A state machine must be running on a separate thread. When creating a state machine you must specify which thread it should be running on. The system can correspond to the whole model which can have many state machines inside itself and therefore many threads. Taking the system to a final state can be interpreted as taking the “master” state machine to a final state. This was how it was interpreted during the pilot and unfortuanately this must have been the reason why Qtronic was not able to generate any test cases using only finalized runs in the pilot. The pilot had only one final state in one of the state machines, the Mobile Stations which is some type of master state machine.

11.1.4 Record and class naming

Record, which is the data type used for sending information in the signals from/to/between state machines and Qtronic, and class names are using the same namespace in QML.

Therefore this is not allowed:

```
record sameName
{
}

Class sameName
{
}
```

This is not a big problem because Qtronic will perform model checking before the test generation is started and tell you that there are multiple declarations.

11.1.5 Only basic types in records

The data type that is allowed in a record is limited. The allowed types are all the primitive types, String type, arrays and other record types.

For example classes are not a valid type so it is not possible to send a reference to an object through a signal.

This example is not valid, because it tries to have a record with a class type:

```
class MultislotClass
{
   ...
}

record createSignal
{
   MultislotClass multislotClass;
}
```

A work around for this can be having an integer in the record that is an identifier to the multi slot class and then have a method in the `MultislotClass` that takes this identifier as an argument and returns a reference to the object.

```
class MultislotClass
{
   ...
}

record createSignal
{
   int multislotClassID;
}
```

11.1.6 Prevent deadlocks

In the beginning of the pilot model, Qtronic had the possibility to send signals directly to the Mobile Stations state machine and the Channel Utilization state machine. When MS sent a TBF request to Connection Control, CC checked the request and sent it to CU. Both MS and

CC were now waiting for CU to perform the best possible reservation. But if Qtronic sent the signal for making a channel faulty before the CU received the request from CC then a possible deadlock could happen.

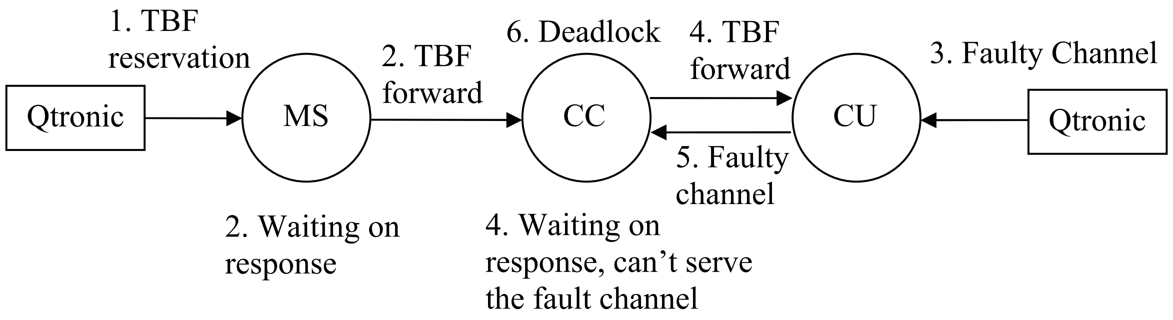


Figure 11.1.2 System deadlock

One way of solving this deadlock problem is to let Qtronic send starting signals to one of the state machines. This is the way that was used in the pilot. Qtronic can send a faulty channel signal when the MS is in a certain state which says that it is not waiting for a TBF response. The MS then forwards this information to CU, which starts a faulty channel.

Other possible solutions can be in letting signals have a timeout, if the state machine does not respond in a certain amount of time it will be timed out. This is a bad solution because Qtronic will find this timeout and will generate a test case for it, and if the system does not have this timeout feature then the behavioral model should not have it either.

11.1.7 Don’t use the trace function

There is a trace function in QML. This function makes it possible to get information from Qtronic during test generation phase. The problem with the trace function is that it will not report anything if something is wrong in the model, it only reports information when everything is working. So the trace function is not a good debugging too, because the trace output is not sent immediately when it is encountered in the code. Instead at some later point and if something is wrong in the model then it will fail before it reaches this output state.

If you are tracing values of signals, it can be very confusing to understand what is happening. This is because two traces do not have to be from same input run. Qtronic inputs a lot of different values to the model for finding good test cases. If you trace these values it easily gets very complicated.

The guideline is to use the trace function sparse or not at all. The only thing that the trace function was used for in the pilot was to control that Qtronic did try to generate test cases. If it did generate any trace printout then something was very wrong in the model, but Qtronic was not able to report it.

11.1.8 Use assertions for finding bugs

A much better way of finding bugs, instead of using the trace function, in the model is to use assert statements in the code. If the assertion is false then Qtronic will directly report the assertion and stop the test generation phase. Qtronic will show the stack trace with the latest signals and their value, this makes it easier to understand what happened.

11.1.9 Self-loops with no signal on the transition

Building a state machine that has a self-loop with no signal on the self-loop transition is something that should be avoided.

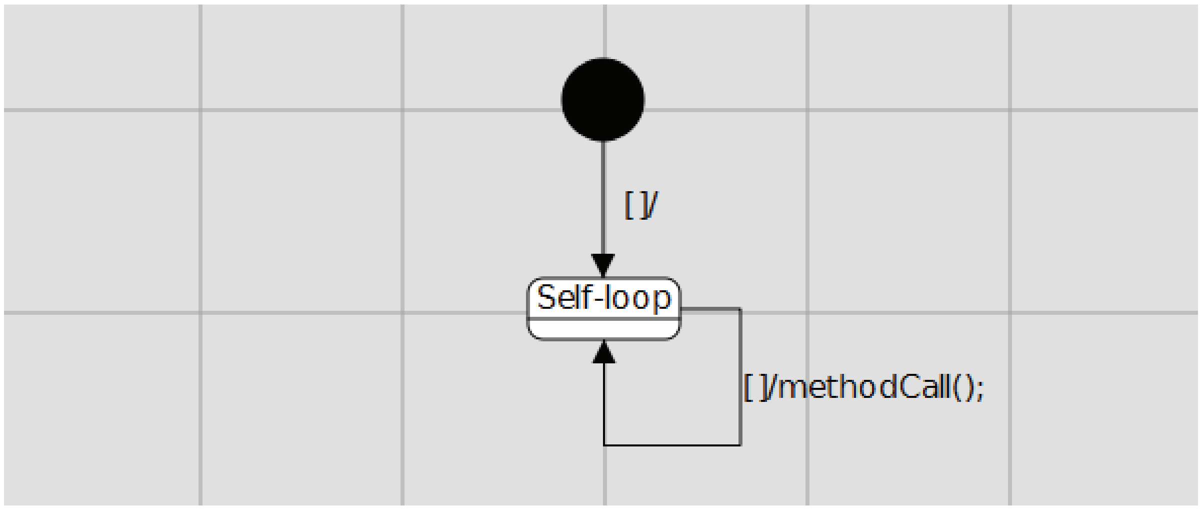


Figure 11.1.3 State machine with self-loop without a signal

In general this is called the halting problem, which is a problem that is unsolvable. It has been proven that it is impossible to decide if a program in general will halt or not. If a state machine like this is given to Qtronic, then it will loop forever and growing in memory size until the Operating System (OS) decides that it is time to kill the Qtronic process.

11.2 Found bugs in Qtronic

During the pilot some bugs were found in the Conformiq Qtronic program. All of them have been reported to Conformiq, one of them have been fixed in the version 1.3.0. The other ones will hopefully be corrected in the next Qtronic release.

11.2.1 Self-loops

This bug was found when the model of the neighboring cell files was created. At the time the Qtronic 1.2.1 was the newest available version. The problem was that Qtronic was not able to generate any test cases when the state machine looked like the top one, but if the state machine was like the bottom one then Qtronic was able to generate test cases.

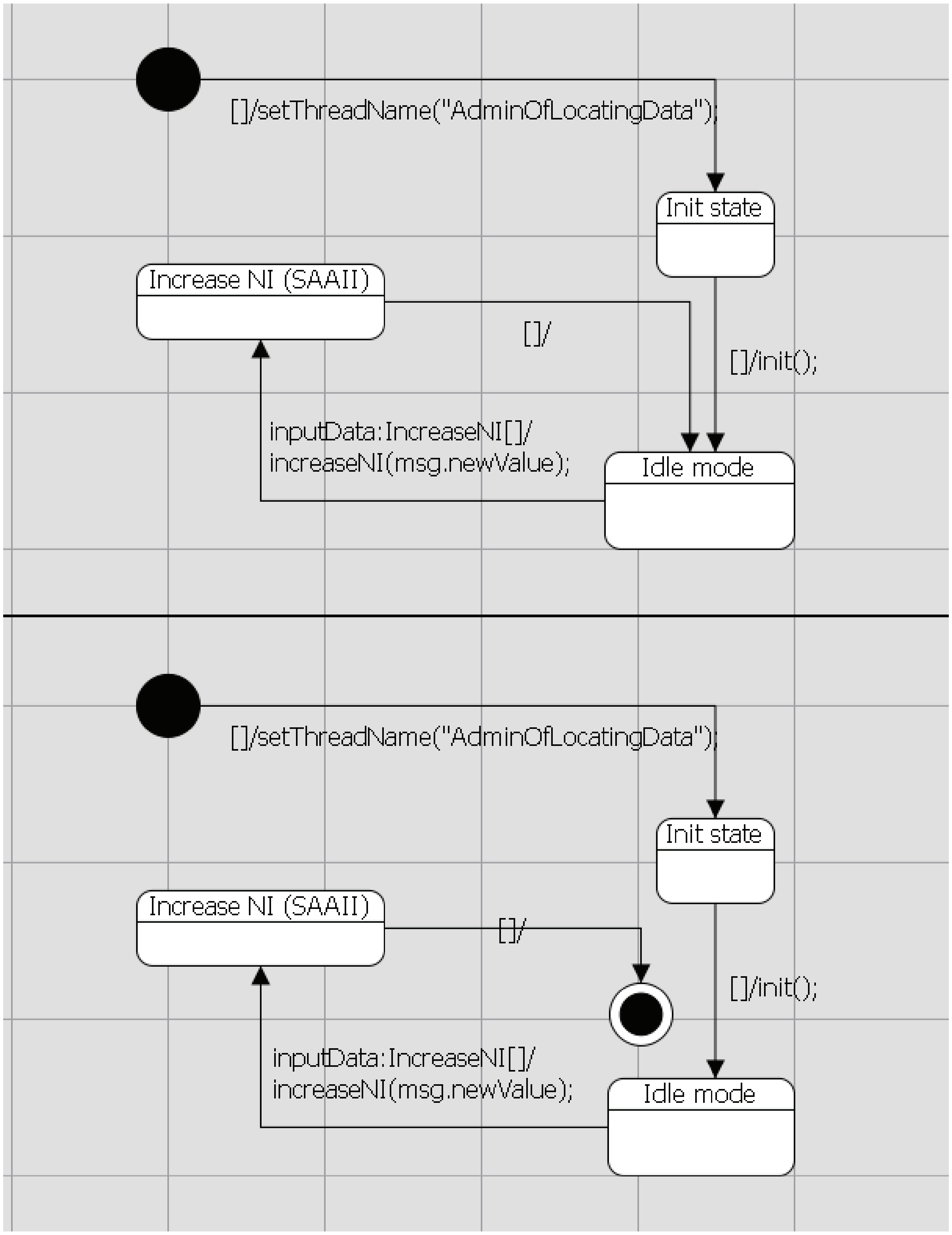


Figure 11.2.1 Self-loop making Qtronic unable to generate test cases

There was no change to the action language code, so the problem was the self-loop. This self-loop is not the same type as the self-loop described in section 11.1.9.

Qtronic was given this simple model that showed the bug and updated Qtronic and released a new version in just one week, which was very good.

11.2.2 Qtronic signal value as argument to a method

In the state machine Channel Utilization in the pilot, there is a method `saveTBF(.. ,int multislotClassId, ..)` that saves the properties of the TBF request so that CU can use them in a later stage.

```
class CU extends StateMachine
{
 public CU(...)
 {
   msClasses = new MultislotClasses();
   msClasses.init();
 }

 ...

 private void saveTBF(... , int multislotClassId, ...)
 {
   TBFMultislotClass = msClasses.getMultislotClass(multislotClassId);
 }

 private void checkCriteria()
 {
   int sum;

   sum = TBFMultislotClass.getDL();
 }

 ...

 private MultislotClasses msClasses;
 private MultislotClass TBFMultislotClass;
}
```

The method `saveTBF` gets its parameters through a signal from the state machine Connection Control. The bug in Qtronic is that the signal variable `multislotClassId` can't be used as an in parameter to the method `getMultislotClass(int ID)`.

When Qtronic was doing the test generation phase it took ages to finish this phase, and the result was that it was not able to cover the method `checkCriteria()`.

The first attempt was to insert a trace in checkCriteria() to see if Qtronic did try to cover this method

```
private void checkCriteria()
{
   trace("Inside checkCriteria");
   int sum;

   sum = TBFMultislotClass.getDL();
}
```

Qtronic did not output the trace at all. The problem with the trace is that it does not output when the trace is executed, but it is do in some later stage. This was not known at that time.

The next step was to insert an assertion in the `checkCriteria` instead.

```
private void checkCriteria()
{
   assert(TBFMultislotClass instanceof MultislotClass);
   int sum;
   sum = TBFMultislotClass.getDL();
}
```

This assertion failed! How could that happen? The variable TBFMultislotClass was declared in the class scope, so it was visible inside `checkCriteria` method.

The saveTBF method was updated so that the input to the `getMultislotClass` was always 0.

```
private void saveTBF(... , int multislotClassId, ...)
{
   TBFMultislotClass = msClasses.getMultislotClass(0);
}
```

This worked totally fine and Qtronic was able to cover the `checkCriteria` method.

The final working solution for this bug was:

```
private void saveTBF(... , int multislotClassId, ...)
{
   if (multislotClassId == 0)
     TBFMultislotClass = msClasses.getMultislotClass(0);
   else if (multislotClassId == 1)
     TBFMultislotClass = msClasses.getMultislotClass(1);
   ...
}
```

So if the value of `multislotClassId` was used directly then it did not work, but if a static value was used then it worked fine. The signal value was destroyed in some way when it was passed to `getMultislotClass`.

11.2.3 Vector position 13

The class `MultislotClasses` has a vector which is used for saving a reference to a `MultislotClass`. The initiation of the vector is done in the `init` method.

```
class MultislotClasses
{
 public MultislotClasses() { }

 public void init()
 {
   msClasses = new Vector<MultislotClass>();

   MultislotClass multislotObj;
   int id = -1;

   // Multislot Class 0
   id++;
   multislotObj = new MultislotClass(id,1,1,1);
   msClasses.add(multislotObj);

   // Multislot Class 1
   id++;
   multislotObj = new MultislotClass(id,1,1,1);
   msClasses.add(multislotObj);

   ...


   // Qtronic can't use position 13 in the vector

   // Multislot Class 31 (is in position 13)
   id++;
   multislotObj = new MultislotClass(31,5,2,6);
   msClasses.add(multislotObj);
 }

 private Vector<MultislotClass> msClasses;
}
```

The `init` method instantiate all multi slot classes, totally there are 14 multi slot classes in the `msClasses` vector.

Multi slot Class 31 has 5 downlinks and 2 uplinks but can only use 6 of the links simultaneously. This multi slot class must be used for setting up a RTTI connection with 4 downlinks and 2 uplinks.

When this multi slot class was in position thirteen in the vector, then Qtronic was not able to produce a test case that had 4 downlinks and 2 uplinks. This was really strange, and just for testing position number 12 was changed to have to be multi slot class 31 also. When this was done Qtronic was able to generate a test case with 4 downlinks and 2 uplinks.

Vector position number 13 is not a good position to use, which is quite funny because it is the unlucky number.

11.2.4 Long text string in signal value

The Channel Utilization state machine has a frame that have a number of timeslots. For verifying that the model did what it was intended to do a method was created that printed out the current state of one of the timeslots. This method was called for each timeslot in the frame and then the result was outputted using a signal.

```
public String printTimeSlotAllInfo(int timeSlotId)
{
   TimeSlot timeSlot = frame.get(timeSlotId);

   return " " + timeSlot.getPDCHType() + ",Ess:" + timeSlot.isEssential()

   + "," + timeSlot.getTTIMode() + " ";


   //return " " + timeSlot.getPDCHType() + ",MS:" + timeSlot.getMSId() +

   //",DL:" + timeSlot.isDL() + ",UL:" + timeSlot.isUL() + ",Ess:" +
   //timeSlot.isEssential() + "," + timeSlot.getTTIMode() + " ";

}
```

If the method only outputted a few of the variables in the timeslot then the import model phase in Qtronic was very fast, took almost no time at all. But if the method outputted variables above a certain amount, if was of no importance which of the variables that was used the only thing that mattered was how long the return String was, then Qtronic had big troubles in performing the import of the model, more exactly the *Apply model transformations* phase. Qtronic was able to the import the model but each time it took at least 1 hour, no errors were reported and the test generation worked fine so there was no fault really.

A lot of time was spent on just doing the import of the model. If it takes one hour for each change in the model you get many hours in the end.

11.2.5 Qtronic trace() function

Using a lot of traces in the code seems to make the Apply model transformations stage in the import model phase in Qtronic a bit more time consuming. It is not as bad as in the previous section, and maybe it should be like this. Anyway it is good to know that the import time can increase when the trace function is used.

11.3 Suggestions of improvements of the Qtronic tool

The Qtronic tool is a great tool in many ways. It solves a very challenging task, receiving a general model, examining it and generating interesting test cases from the model.

The big problem with Qtronic is that is very hard to debug the model, when there are faults in it. To find a defect in the model, Qtronic needs to analyze the model and generate test cases. This test generation is often very time consuming. During the test generation phase of the pilot three computers where used for to find errors in the model. Qtronic takes almost 100% of the CPU capacity when it is looking for interesting test cases, so the computer is unable to perform anything else thing at the same time.

Because of the extremely long time it takes to generate test cases, 15 hours were quite normal, the pilot took longer time than planned. It would be good if something could be done in the Qtronic program to reduce time dramatically.

The Qtronic version 1.3.1 has a new feature that saves the old test cases (assets) and tries to use these test cases the next time a test generation is performed. If some part of the model has not been changed then the assets will be used again and Qtronic will be able to do a much better performance regarding to time. The first time you do it still takes very long time.

11.3.1 Eclipse integration

In this pilot the Eclipse Platform has been used for writing the action language code. The QML follows the java language syntax in many ways, but it also has its differences. It has been quite annoying that the Eclipse indicates that you are writing something in the wrong way when you are not.

It would be good if Qtronic would support some plug-in that makes Eclipse understand the Qtronic Modeling Language (QML).

11.3.2 Viewing a test case trace in the model

The best way of viewing the generated test cases from Qtronic is by using the HTML Script Generator. This script generator gives a graphical overview of the generated test cases. It is quite easy to follow each test case if you know how the model is built.

The problem comes when the person that is viewing the test cases does not know the exact implementation of the model. This problem could easily be solved by introducing a new type of test case trace that made it possible to directly single step the model with each test case. When a test case is examined it should be possible to follow its propagation through the model. It should be indicated when a transition is taken and which is the current state in the state machine.

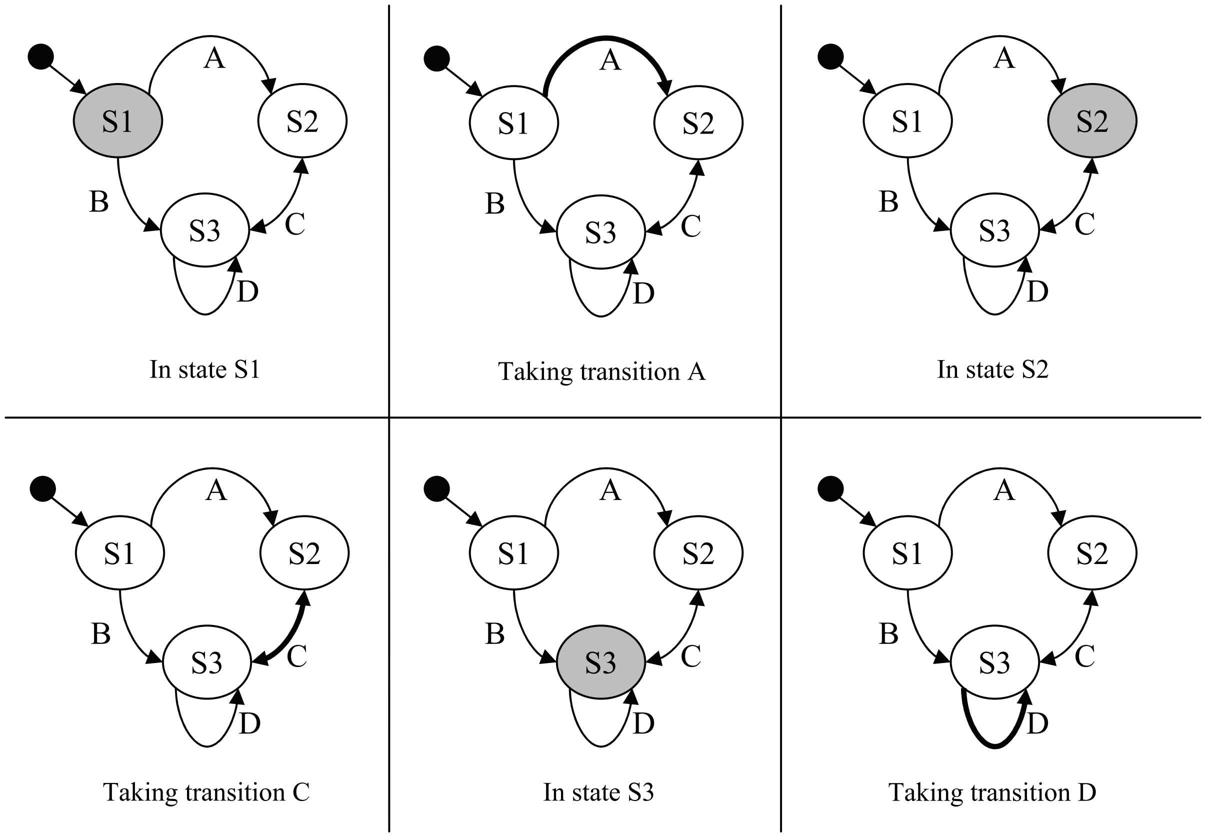


Figure 11.3.1 Traceable test cases in the model

This feature would also improve the traceability and understanding of the model.

11.3.3 Debugging

The main problem with Qtronic is the debugging of the model and the large amount of time that is needed for test generation when the debugging is done. It would be good if Qtronic had a debugging mode, where you could specify exactly which part of the model that you want to test.

Now you are able to insert requirements to the model and in the Qtronic tool select or deselects these requirements. By doing so you are guiding Qtronic in which way you want your test cases. The problem with requirements is that Qtronic need a QML Model Coverage, e.g. state coverage, to be able to cover a requirement. When selecting a model coverage principle Qtronic will try and cover the whole coverage principle not only the requirement. So Qtronic will do things that you don't want to test when you are debugging and this is waste of time.

It would be good if Qtronic could show a tree structure (with states, transitions, methods and requirements) of the model and by clicking in a node in the tree would enable Qtronic to try and cover only this part. Qtronic should use whatever coverage it wants, the only thing that is of interest is making sure that the node is reachable. When the node is reached Qtronic should stop the test generation. This would really speed up the debugging of the model.

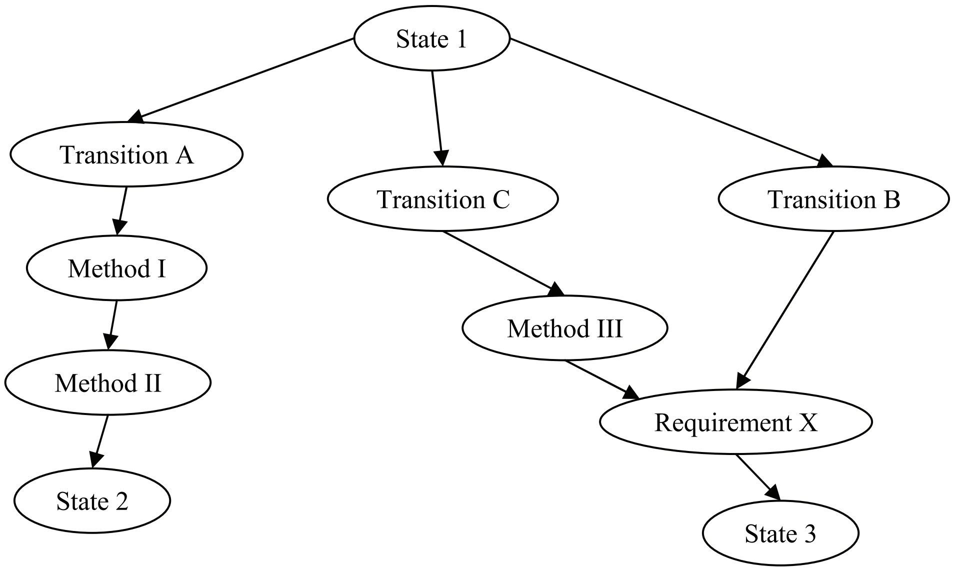


Figure 11.3.2 Sketch of new debugging feature

For example if you want to test and debug the `Method II` then you select this node in the tree and Qtronic tries to cover this method. The path that Qtronic should walk is `State 1`, `Transition A`, `Method I` and `Method II`. No other path in the model should be walked.

11.3.4 Randomize the none important input values selection

It seems that when Qtronic is creating test cases it always tries to select the simplest possible input parameters. If some input parameter is not really important for the specific test cases then Qtronic selects the simplest (lowest) value in the allowed range. This is absolutly the simplest way when implementing Qtronic but using a smarter selection choice would improve the coverage on the model.

This figure shows how Qtronic choose to select the multi slot classes in the test cases:

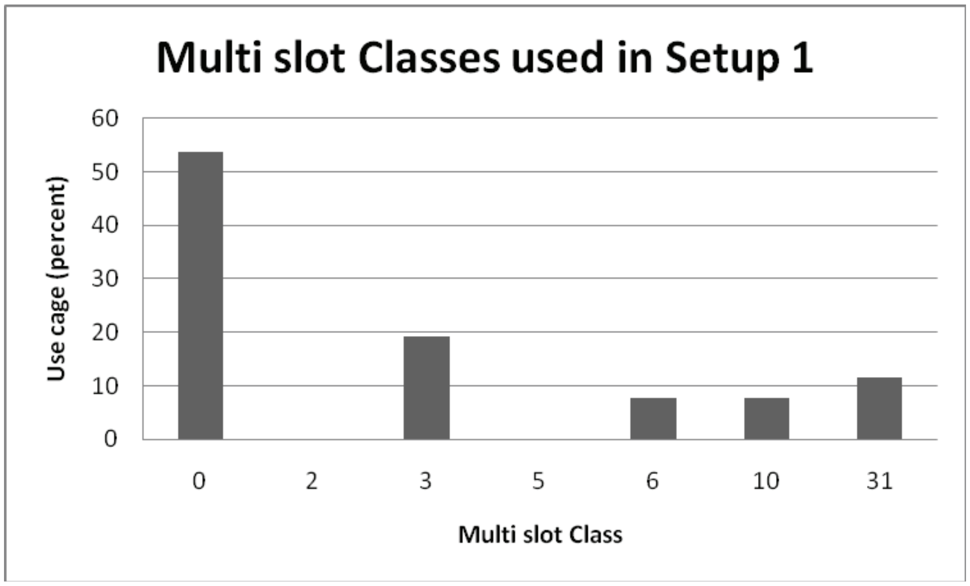


Figure 11.3.3 Use cage of multi slot classes in different test cases

Multi slot class 0 is used much more than the other multi slot classes, and multi slot class 2 and 5 is never used at all. This is because Qtronic didn't think it was important to test these multi slot classes. It would have been better if Qtronic tried to distribute the none important input parameters over the whole input range instead of always selecting the easiest choice. This can be accomplished by using e.g. random-value coverage. Then the unmeasured coverage that Qtronic does not measure would be improved. Some of the test cases that used multi slot class 0 could instead used multi slot class 2 or some other multi slot class. As it is now it can be an error when using multi slot class 2 and Qtronic would not be able to find it.

11.3.5 Using idle computers for test generation

Finding interesting test cases from a behavioral model is a computationally intensive task. One way of gaining more computation power is to have a cluster or some other type of ad hoc network of computers.

Very often a computer in an office network is idle, maybe the user is in a meeting, is having a break or is just writing or coding something that is not so computation intensive.

Every computer in the network has a small Qtronic program that monitor how hard the computer is working for the moment. If one of the computers is doing a test generation execution then it can borrow computation power from other idle computers in the network.

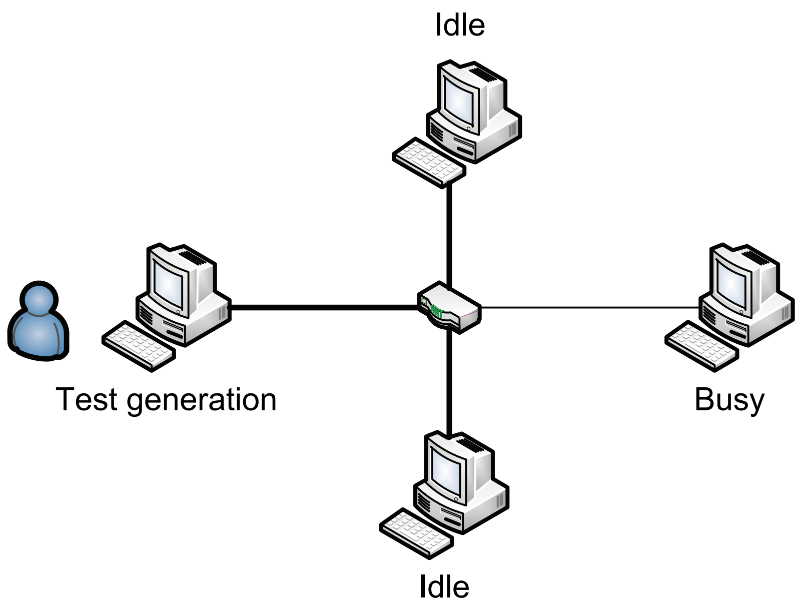


Figure 11.3.4 Use idle computer for test generation

12 Conclusion and future work

This chapter tries to summarize the thoughts that are in this report and also tries to give a final conclusion on what to do next.

12.1 Conclusion

In model-based testing the main thing is to build a behavioral model of the system that you are testing. It is important that you put all your effort in figuring out which part of the system that is important to test. The parts that need to be deeply tested must have a lot of details in the model to give the test generation tool a good chance to perform a good job. If the model is very detailed then it will lead to longer time needed in all stages in the MBT process; building the model, debugging, generating test cases.

Model-based testing is a black-box technique and therefore it is suited for deploying in an early phase of the implementation process. It is suggested that the behavioral model should be a collaboration between the design team and the test team. The model would then be the point that unites the two teams. This is one of the great things the model-based testing approaches.

If the model is built in an early stage then it will help in finding defects in the Implement Proposal or ambiguous requirements.

The model will help in finding omissions, contradictions and unclear requirements. If a requirement is unclear when producing the model then it needs to be address to be able to proceed with the work. The test scope will always be up to date even if some requirements change. When a requirement changes all that needs to be updated is the model itself and this should be an easier task then examine all test cases and change them as needed in manual testing.

A problem will arise if the entire MBT process will not be used. In the manual testing process used by BSC Design all test cases are given an informative name that tells what the test case is testing. This naming is not supported by Qtronic so this will need to be a manual step in the process. If something changes in the model then a new test suite will be generated, and some test cases will likely be changed and then the new test case will get a name. There will also be a problem with knowing which test case that is new and which is old. This will unfortunately lead to longer time needed in the testing stage than if the whole MBT process would be introduced.

The model-based testing process will introduce more error sources compared with the manual testing. The introduced behavioral model can introduce errors, the adaptor layer between the test generation tool and the test cases can have faults and the adaptor layer between the test cases and the system under test can also have faults. Therefore it will be more complicated to know where the fault is. In manual testing the fault is either in the test case or in the system.

All parts of a system are not suitable for model-based testing. If it is easier to cover some part of the model by just doing some easy manual testing then it should be done. Often it is needed some surrounding things around the model to get it work, e.g. structures for saving values. If the part should be tested is very straight forward, e.g. testing that a command output is in the correct way, then it is better to just to do a manual test case for this part, instead of creating a model and only get this test case.

The result from the pilot shows that the expert group thinks that model-based testing is a very interesting approach. The method didn't get magnificent better result than the manual testing approach, but the result were not worse than manual testing.

During the pilot some problems occurred, some of them were because the Qtronic manual had some faults or didn't explain some parts in a good way. Most of the manual was well written.

The biggest problem with Qtronic is that it is hard to do debugging in an efficient way. The model is created by a human being and therefore error or mistakes will be introduced in the model. Qtronic provide excellent debugging information sometimes, e.g. reporting when a possible deadlock can occur in the model. But sometimes the information that is given from Qtronic is really weak or none at all and it only reports that it was unable to cover some part of the model. It would be very helpful to know what type of inputs it tried and maybe letting the Qtronic user to select some inputs that help test generation process. Sometimes it is hard to know if it is a real fault in the model or if Qtronic didn't have the power to cover some part of the model.

It is the writer's believe that Conformiq should implement a debugging feature like the one that is proposed in section 11.3.3. This is because a lot of time had to be spent on debugging the pilot model. Each test generation took from 30 minutes to 20 hours to perform. To be able to find an defect in the model or in Qtronic a test generation had to be performed and waiting this amount of time for debugging a defect was not really so productive.

12.2 Future work, next step

What happens if MBT process is used all the way? When error reports come back from the users/operators of the BSC, will it then be possible to use the models then or had it been easier to look at old test cases?

Can you rely on that the test cases generated by the test generation tool are so good that you don't need to examine them? If the answer is no, then the MBT process will need both an inspection on the model and then an inspection on the generated test cases. This will increase the needed inspection work regarding to manual testing.

Another interesting thing to examine would be to see if it is possible to integrate the Qtronic tool to BSC testing flow.

There are numerous of practical questions that need to be addressed, e.g. how to organize the models, use reference models or build a new model for each new feature etc. Having reference models seems to be a good thing, but maybe the state space explosion problem, section 4.5.3, will make it impossible to do.

The next step can be to do a larger pilot with model-based testing, either some half measure using the model and then the normal manual process or using the entire model-based testing process with automatic test execution.

References

Abran, Alain; Moore, James W. (2004), *Software Engineering Body of Knowledge (SWEBOK)*. [www] <http://www.swebok.org> 2008-02-04

Beizer, Boris (1995); *Black-Box Testing: Techniques for Functional Testing of Software and Systems*. New York: Wiley, cop. ISBN: 0-471-12094-4

Beizer, Boris (1990); *Software Testing Techniques*. Second Edition. International Thomson Computer Press. ISBN: 1-850-32880-3

Blackburn, M.; Busser, R.; Nauman A. (2004); *Why Model-Based Test Automation is Different and What You Should Know to Get Started*. Software Productivity Consortium, NFP.

Conformiq (2008); *Conformiq Qtronic Evaluation Guide*.

Conformiq (2008); *Conformiq Qtronic: Semantics and Algorithms.*

Conformiq (2008); *Conformiq Qtronic User Manual*.

Cornett, Steve (2007); *Code Coverage Analysis*. [www] <http://www.bullseye.com/coverage.html> 2008-02-29

Dalal, S.R.; Jain, A.; Karunanithi, N.; Leaton, J.M.; Lott, C.M.; Patton, G.C.; Horowitz, B.M. (1999); *Model-based testing in practice*. IEEE: 10.1109/ICSE.1999.841019

Ericsson AB (2003), *Ericsson Product Training/GSM Radio Network Overview* [www] <Internal> (2008-04-21)

El-Far, I. K.; Whittaker, J. A. (2002); Model-based Software Testing. In Marciniak, J. (ed.), *Encyclopedia on Software Engineering*, Volume 1. Wiley-InterScience. ISBN 0-471-21008-0

Huima, Antti (2007); *Implementing Conformiq Qtronic*.

Lamsweerde, Axel van (2000); *Formal Specification: a Roadmap*. ACM: 1-58113-253-0/00/6

McQuillan, Jacqueline A.; Power, James F. (2005); *A Survey of UML-Based Coverage Criteria for Software Testing.* Technical report NUIM-CS-TR-2005-08, Department of Computer Science, NUI Maynooth, Ireland

Mellor, Stephen J. (2002); *Executable UML: a foundation for model-driven architecture*. Boston: Addison-Wesley. ISBN: 0-201-74804-5

Naughton, Patrick (1996); *The Java handbook*. Berkeley, California, Osborne McGraw – Hill, cop. ISBN: 0-078-82199-1

Ryber, Torbjörn (2007); *Essential Software Test Design*. Fearless Consulting. ISBN: 9-185-69903-9

Ryder, Torbjörn (2006); *Testdesign för programvara: Så tar du fram bra testfall*. No Digit Media. ISBN: 9-197-60621-9

SDL Forum Society; *SDL & MSC*. [www] <http://www.sdl-forum.org> 2008-02-26

Svensson, Tomas (1999); *SS7 module testing supported by Java based test tool*. LiTH-IDA-Ex-99/3

Uppsala University; Aalborg University; *UPPAAL*. [www] <http://www.uppaal.com> 2008-02-26

Utting M.; Legeard B. (2006); *Practical Model-Based Testing: A Tools Approach*. Morgan Kaufmann. ISBN: 0-123-72501-1

Xiong, Yiwei; Jefferson Offutt, A.; Liu, Shaoying; *Criteria for Generating Specification-based Tests*. IEEE: 10.1109/ICECCS.1999.802856

Appendix A: Multi slot class table

Multi slot class	*Downlinks*	*Uplinks*	*Sum*
0	1	1	1
2	2	1	3
3	2	2	3
5	2	2	4
6	3	3	4
10	4	2	5
31	5	2	6

Table A.1 Multi slot classes

The downlinks column indicates how many downlink channels a mobile station can have at the most. The uplink column is the same thing but for the uplink direction instead. The sum column says how many downlink and uplink channels the mobile station can have simultaneously, e.g. a mobile station that is multi slot class 0 can only have 1 downlinks or 1 uplink at the same time. This is because the sum is 1.